USE OF RECYCLED CONCRETE MADE WITH FLORIDA LIMESTONE AGGREGATE FOR A BASE COURSE IN FLEXIBLE PAVEMENT

Final Report

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16. Abstract

The objectives of this research study are to investigate the feasibility of using recycled concrete aggregate (RCA) as a base course material in asphalt pavement, to evaluate the physical properties of RCA, and to develop practical and reliable guidelines and specifications. The tasks included in this study are: literature review, a questionnaire to RCA producers, sample collection, laboratory testing, accelerated performance testing and pavement distresses monitoring, Falling Weight Deflectometer (FWD) test, theoretical analysis of pavement, and development of guidelines and specifications for the use of Florida RCA.

The laboratory tests of RCA samples included: gradation, LBR, LA abrasion, soundness and sand equivalent, optimum moisture content, maximum dry unit weight, permeability, and impurities.

The project also included the construction of three test sections of asphalt pavement at the University of Central Florida Circular Accelerated Test Track (UCF-CATT). Two sections of different thickness were constructed with RCA base and one section with limerock (LR) base.

A total of 362,198 load repetitions were applied to the test sections. This is equal to 811,324 of 18 kips (80 kN), equivalent single axle load (ESAL). The pavement distresses of rutting, cracking, and settlement were monitored during the course of the performance testing. Falling Weight Deflectometer (FWD) test was performed on the pavement test sections to back-calculate the in-situ resilient moduli of RCA and LR for theoretical analysis of life expectancy.

The findings in this project support the hypothesis that RCA can be used effectively as a base course when appropriate quality control techniques are utilized. Based on the information obtained in this study, a set of specifications for the use of RCA as a base course in flexible pavements was developed.

17. Key Words

Recycled Concrete Aggregates (RCA), Laboratory properties, FWD test, Accelerated Performance Testing, Pavement Analysis.

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This report is prepared in cooperation with the State of Florida Department of Transportation.

EXECUTIVE SUMMARY

A survey of various U.S. highway agencies showed that there is a great potential for the use of recycled concrete aggregate (RCA) in highway construction. RCA is presently used on a limited basis in pavement bases, concrete shoulder, porous granular fill, and as a portion of the aggregates in new concrete pavement. If RCA is adopted for extensive use as a base course material, replacing the natural aggregates currently used in pavement construction, then the physical and mechanical properties of RCA must be well understood and documented, and standards for its use must be established.

The objectives of this research study are: to investigate the feasibility of using RCA as a base course material in asphalt pavement, to evaluate the physical properties of RCA, and to develop practical and reliable guidelines and specifications.

The tasks included in this study are: literature review, sample collection, laboratory testing, accelerated performance testing and pavement distresses monitoring, Falling Weight Deflectometer (FWD) testing, theoretical analysis of pavement test sections, and development of guidelines and specifications for the use of Florida RCA.

The following is a summary of the results obtained from this research project:

<u>Literature Review</u>

A review of the existing literature about RCA revealed that its qualities are slightly lower than the qualities of virgin aggregates (VA) due to the cement

attached to the stone aggregate. The literature review also revealed that some countries such as Germany, England, Japan, as well as the United States have developed some guidelines and specifications for the use of RCA.

Information from the literature review suggests that in comparison to VA, RCA has more angular particles, a higher water absorption rate, a higher abrasion value, a lower compressive strength, and a lower modulus of elasticity.

RCA Producer Survey

A survey of RCA producers was conducted relative to production method, use, and cost. A total of fifteen companies representing the 75% of the concerns surveyed (population) responded to questionnaire. The survey responses are presented in Chapter 3.

Laboratory Testing

Results of the gradation analysis indicated that the particle size distribution is one of the important factors for the selection of RCA materials. The average gradation of most of the samples collected from the sites located at FDOT districts met the requirements established in the FDOT Section 204 (Graded Aggregate Base) with the exception for the materials from Districts 2 and 6.

The results from the limerock-bearing ratio (LBR) test show that the arithmetic mean of the LBR value including outlier (181.53) surpasses the LBR 100 of VA required by FDOT. This indicates that a well-processed RCA is an acceptable material for use as a base course in pavement construction.

The results of the Los Angeles Abrasion test show that the ranges of LA abrasion losses for the RCA samples in this study were 41.1% to 47.60%. LA abrasion loses of less than 45% is specified by FDOT Section 204 for natural aggregates.

Sodium sulfate tests conducted on RCA samples collected in December show a soundness loss much greater than FDOT specifications of 15% after 5 cycles. District 2 had the highest loss at 70%. The average soundness loss is about 52%, well above the FDOT specification.

Every RCA sample tested in this project was found to have sand equivalent much greater than the 28% required by FDOT specifications. The average for all samples is about 70%.

The presence of lead in some RCA samples from Districts 2 and 4 suggests the possible presence of lead-paint in old demolished concrete. The highest computed lead content was 12ppm from District 4 samples, which is clearly over the 5ppm EPA limit. The laboratory analytical results indicated that asbestos fibers were not detected in any of the samples.

The results of maximum dry unit weights and optimum moisture contents by compaction tests, conducted simultaneously at UCF and FDOT District 5 laboratory. The average maximum dry unit weight was 113.8 lb/ft^3 (17.9 kN/m^3) from UCF and 114.8 lb/ft^3 (18.1 kN/m^3) from FDOT-District 5, with corresponding average optimum moisture content of 11.2% and 12.1% respectively. One RCA sample from District 6 obtained a maximum dry unit weight of 103.2 lb/ft^3

($16.2kN/m^3$). This sample contained a large amount of foreign materials the data is considered as an outlier.

The average RCA permeability from all RCA samples was 0.67 ft/day (2.4 x 10^{-4} cm/s), which exceeds the 0.283 ft/day (10^{-4} cm/s) recommended by Senior (1992).

The average impurity content from all RCA samples was found to be 3.67% with District 6 samples included and 1.99% without District 6 samples. The samples from District 6 were not acceptable for base course due to the high content of foreign materials.

Performance of The Test Sections

Three test sections were constructed at the UCF Accelerated Test Track to conduct the performance tests of base courses within the flexible pavement system. Section 1 was constructed with an 8 in. (20.3 cm) thick RCA base, and section 2 was constructed with a 10½ in. (26.7 cm) thick RCA base, while section 3 was constructed with a 10½ in. (26.7 cm) thick limerock base. All three test sections were covered by 4 in. (20.2 cm) of FDOT specified S-1 asphalt concrete paved by Orlando Paving Company in Orlando, FL.

A dual wheel load of 11,000 lbs (48.9 kN) or 22,000 lbs (98 kN) per axle was applied on the three test sections. A total of 362,198 load repetitions, which would represent a pavement life expectancy of over 37 years, were applied on the test track. As a result of this study, pavement sections with RCA base appeared to demonstrate better performance than the limerock base control section.

The pavement distresses were monitored during the course of performance testing. The distresses were measured for rutting, cracking, and settlement.

No rutting was observed in any of the test sections. This was supported by surface level measurements between the outside and the inside wheel paths, with the exception of surface wear directly under the wheel path.

A total of 16 transverse cracks and one longitudinal crack appeared along the wheel path in the limerock section. No cracks were observed in either RCA test section.

There were two distinct settlements, both of which occurred at both ends of test sections 1 and 3 connected to the concrete slab of the two bridge decks. The settlement in the limerock section was measured to be 1¾ in. (4.5cm) as compared to ¾ in. (2.0cm) in the RCA sections.

Theoretical Analysis

Falling Weight Deflectometer tests (FWD) were performed on the test sections at the beginning and at the end of the performance tests. The results of the FWD deflection data along with deflection basin are presented in Chapter 6

KENLAYER program was employed to back-calculate the modulus of elasticity of the bonded RCA base material, as well as, Limerock by using the load-deflection data obtained from the FWD test. A modulus of elasticity of 380,000psi (55,112 kPa) for asphalt concrete was the average laboratory test result obtained by the University of Florida from the test track core samples.

In-situ moduli of the layer components that best fit to the deflection basins at test sections 1,2 and 3 were found to be; E_{RCA} = 195,000psi (28,281 kPa), E_{LR} =60,000psi (8,702 kPa), and E_{subg}= 30,000psi (4,350 kPa) respectively. The resilient modulus of RCA obtained from this analysis is comparable to the test results obtained from the Test Pit conducted by FDOT Materials Office in Gainesville (203,215 psi at 10.5 in. RCA at 100 cycles to 111,768 at 30,000 cycles)

The evaluation of the allowable number of 22 kips (98 kN) load repetitions for fatigue (N_f) and rutting (N_d) failures in RCA test sections are 39.34 X 10^{6} and 1.8 X 10^{6} for section 1, and 45.30 X 10^{6} and 6.9 X 10^{6} for section 2 respectively. Since, N_f and N_d are extremely high, neither RCA section 1 or 2 would fail in fatigue and rutting.

By assuming that an average daily traffic (ADT) volume of 7,500 in one direction for typical medium-heavy highway traffic with an average 6% of 18 kips (80 kN) truck, the 362,198 load repetitions of accelerated testing is equivalent to 36.9 years of life expectancy for the RCA pavement test sections.

Structural Layer Coefficients and Thickness Design

The structural layer coefficients of asphalt concrete, a_1, RCA, a_{2RCA}, and limerock, a_{2LR}, computed by the resilient moduli as determined by the test sections are, respectively:

$$a_1 = 0.42 \qquad a_{2RCA} = 0.34 \qquad a_{2LR} = 0.213$$

While the structural layer coefficients of RCA and limerock computed by CBR via LBR are, respectively:

$a_{2LR} = 0.14$ (Limerock from FDOT Test Pit)

$a_{2RCA} = 0.17$ (RCA from Test Section)

$a_{2RCA} = 0.16$ (RCA from all samples except district 6)

If a conservative structural number of 3.0 and layer coefficients of 1.6 and 1.4 for RCA and limerock are used for the design of the base course, the thickness of RCA base and limerock base would be required a minimum of 8 in. (20.4 cm) and 10.5 in. (26.7 cm). Based on the LBR values, the thickness equivalency of RCA to limerock can be estimated as:

$$H_{RCA} = (0.16 / 0.14)\ H_{LR} = 1.1\ H_{LR}$$

This means that 1.0 in. (2.54 cm) of RCA will be equivalent to 1.1 in. (2.8 cm) of limerock. The above-calculated figures are based solely on the results of this study.

Guidelines and Specifications

Based on the results of this study, the proposed guidelines and recommendations for the selection and use of RCA as a base course in flexible pavements are presented in Chapter 8. A proposed RCA specification is also summarized in Table 8.1.

The findings of this project are supportive of the hypothesis that recycled concrete aggregate can be used effectively as a base course when quality control techniques are utilized.

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CHAPTER 1

INTRODUCTION

Continuous urban and industrial development has created the need for more construction materials. Portland Cement Concrete (PCC) is the dominant construction material for buildings, roads, and other structures. PCC products require the admixture of coarse and fine aggregates that must comply with the provisions of existing regulations for concrete mixes. The demand for natural aggregate (NA) has caused an increase in the exploitation of aggregate sources that eventually will lead to their scarcity. For instance, in 1996 the production of crushed stone to be used as virgin aggregate amounted to 2.2 billion metric tons (Grogan, 1996). Concrete technology must consider the need for preserving natural resources from exhaustion and find proper ways to reuse construction waste materials.

The disposal of demolished concrete from old structures in landfills is currently an unfavorable strategy because of the declining availability of disposal space, the increasing cost of disposal, and other environmental concerns. Recycling of old structures as construction materials is a viable alternative. A survey of various U.S. highway agencies showed that many states recognize the great potential for the use of recycled concrete aggregate (RCA) in highway construction. At present RCA is limited to use in pavement bases, concrete shoulder, porous granular fill, and as a portion of the aggregates in new concrete pavement. If RCA is adopted for extensive use as a base course material, replacing the natural aggregates currently used in pavement construction, then the physical and mechanical properties of RCA must be standardized and documented, and the guidelines for applications must be established. The performance of RCA used in pavement must be assured to be better or equal to the performance of virgin aggregates.

Research is needed to evaluate RCA materials and establish application procedures for pavement design. The results obtained from this research study can establish guidelines and specifications that will enable recycled concrete products to be utilized with confidence.

The Florida Department of Transportation (FDOT) sponsored a research project during fiscal year 1996-1997 to develop guidelines and specifications for the use of RCA as concrete mixture and base course for new concrete pavement. The RCA used in that project was obtained from the demolition of old PCC pavement from I-10 near Pensacola, Florida. The old PCC aggregate was mainly river gravel with a specific gravity of 2.6, which is different than limestone. Limestone was the primary coarse aggregate used in the mixture of concrete pavements in central and south Florida. Data regarding the performance of recycled concrete made with Florida limestone aggregate for a base course in flexible pavement are very limited. For that reason, the aggregate industry representatives strongly recommended the use of RCA for any pavement system in Central and South Florida, and further study is needed.

In order to facilitate the preparation of guidelines for the use of RCA as base course for pavements, the following research objectives were proposed:

1. Investigate the feasibility of using RCA made with Florida limestone aggregate (called Florida RCA) for a base course in asphalt pavement including its thickness design.
2. Evaluate the physical properties of Florida RCA including the density, permeability, Limerock Bearing Ratio (LBR), Los Angeles (LA) abrasion loss, Resilient Modulus (M_R), impurities and others.
3. Correlate the RCA test data conducted by test pit program from FDOT Materials Office in Gainesville with the data obtained in this research study.
4. Develop practical and reliable guidelines and specifications for use of Florida RCA.

The following tasks were also performed to achieve the objectives of the study:

1. Literature review of previous work.
2. Identification of demolished concrete pavement samples with known mix design data and the contents of Florida RCA provided by RCA producers in Central Florida.
3. Performance of laboratory test on RCA samples to determine their gradation, particle shape, LBR, LA abrasion loss, absorption, surface soundness, impurities, optimum moisture content, maximum dry density, and hydraulic conductivity (permeability).

4. A large-scale accelerated performance test at the University of Central Florida Circular Accelerated Test Track (UCF-CATT) on three test sections (two RCA sections and one limerock) under a dual wheel loading of 11,000 lbs (48.9 KN).
5. Measurements of pavement deflection at the UCF test sections using a Falling Weight Deflectometer (FWD), and back calculating in-situ modulus of pavement components.
6. Monitoring of pavement distresses during the performance testing for a total over 362,000 load applications that simulated to a life expectancy of over 20 years.
7. Development of guidelines and specifications for the use of Florida RCA as a base course in flexible pavements.

The objective of the accelerated pavement testing at the test track was to evaluate the performance of two RCA test sections through both theoretical and experimental analysis, and to compare the relative performance of pavement systems made with RCA base and limerock base. For analytical approach, the KENLAYER computer program was utilized to determine the tensile strain at the bottom of the Hot Mix Asphalt (HMA) and the compressive strain at the top of the subgrade. The parameters were then used to estimate the theoretical number of allowable repetitions to fatigue and rutting failures in the bonded pavement components. During testing, each test section was monitored closely to detect any signs of distress. The sum of load applications endured on the pavement was used to equate the simulated life expectancy (SLE) of the RCA pavement system.

A questionnaire focusing on procedures and special requirements for selection, transportation, storage, and application of RCA was also developed for the purpose of professional interviews. RCA producers were interviewed by telephone to determine their perception and general experience with RCA material.

CHAPTER 2

LITERATURE REVIEW

The subjects presented in this chapter involve topics related to the properties of aggregates derived from crushed concrete, properties of concrete made with recycled aggregates, and methods used to process the construction waste material. It also includes a review of results obtained from other researchers, the guidelines and specifications developed for different institutions regarding the use of recycled concrete aggregates (RCA). The data compiled consists of both laboratory and field study.

2.1 RCA Origin

RCA is fundamentally a material obtained from the demolition of old concrete structures such as buildings, roads, runways, and other structures. RCA is generally obtained from existing Portland cement concrete curb, sidewalk and driveway sections that may or may not be reinforced. If reinforcing steel exists in the rubble, magnetic separators used in the recovering operation are capable of removing it without much difficulty. However, if welded wire mesh is found in the demolished concrete structure, it may be difficult or impossible to remove it completely. In this case, RCA may contain some metal debris (Federal Highway Administration, 1997).

By definition, RCA is a material composed by nearly 60 to 75 percent high quality, well-graded aggregates bonded by a hardened cementable paste. RCA may include 10 to 30 percent sub-base soil materials and asphalt from either the shoulder or composite pavement. The soil content in RCA usually results from the operation of a backhoe machine, which picks up soil together with concrete during the excavation of the concrete rubble. Therefore, RCA is mainly a mixture of concrete, soil, small amounts of asphalt, and other debris.

In general, the demolished concrete to be recycled is hauled to a central facility for stockpiling and processing. In some large demolition projects, the rubble is processed on site using a mobile plant that crushes, screens, and submits to ferrous metal recovering operations.

2.2 Recycled Concrete Process

Recycled concrete aggregates must fulfill several requirements to be suitable for construction use. They must possess adequate compressive and shear strengths, meet gradation of particle size distribution, and provide proper workability. RCA must not contain harmful impurities such as lead and asbestos, and it must not react with either cement or reinforcement when it is used for concrete admixtures (Guidelines and Specifications for The Use of Recycled Aggregates in Pavements, 1998).

In order to meet the existing guidelines, the construction material recycling industry has developed different approaches for processing concrete and masonry wastes into high quality aggregates. Before processing, the contractor must carefully select the demolished building or other structure and plan to have a separate storage area for the rubbles. The first step in the process is to remove reinforcing steel by using an overhead magnetic separator, then impact mills are used to crush the rubble into various sizes, and finally air classifiers remove lightweight debris such as wood and plastic.

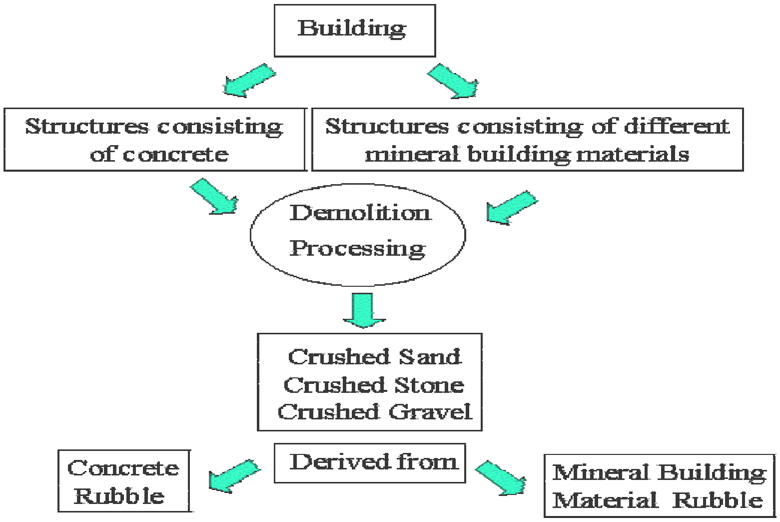
Another important step in the RCA recycling process is the washing of RCA aggregates. Washing is required by some agencies to remove the dust as a measure of reducing potential tufa (porous limestone formed from calcium carbonate) formation. Additional quality control testing may be necessary to estimate the tufa precipitate (leachate) potential of RCA aggregates for embankment applications. In relation to this issue, a special procedure was developed to identify the potential for tufa formation in steel slag that could be used to perform tests on RCA (Federal Highway Administration, 1997).

2.3 Processing Techniques

Since the properties of recycled aggregate depend on the preparation process, special care must to be taken to guarantee its efficiency, so that it mainly influences the particle distribution and the particle shape. For instance, a combination of a jaw crusher in the first hackling phase and a rotating crusher in the second hackling phase yields the best results regarding size distribution and shape. Similarly, the application of wet processing nearly eliminates the harmful substances. Furthermore, the particles will be stripped of crushing dust, which is advantageous for concrete technology.

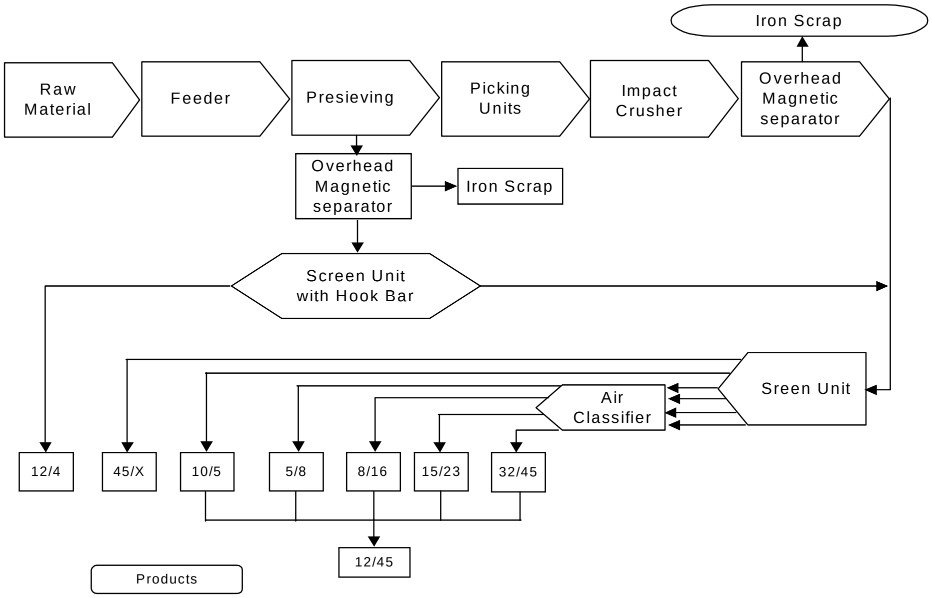
A basic requirement for producing high quality recycled aggregate is the selection of the material entering the preparation process. This presumes a well-organized acceptance and storage of incoming material as well as effective material management. Figure 2.1 illustrates the denomination of different recycled aggregates in Germany (Sustainable Construction, 1998).

One of the techniques used to prepare RCA is the use of picking belts that enable the separation of large substances before raw material with particle sizes greater than 1.77 inches (45 mm) can be transformed into granulate, mainly by impact crushers (Figure 2.2).



Source: Sustainable Construction: Use of Recycled Concrete Aggregate, 1998.

Figure 2.1 Denomination of Recycled Aggregate.



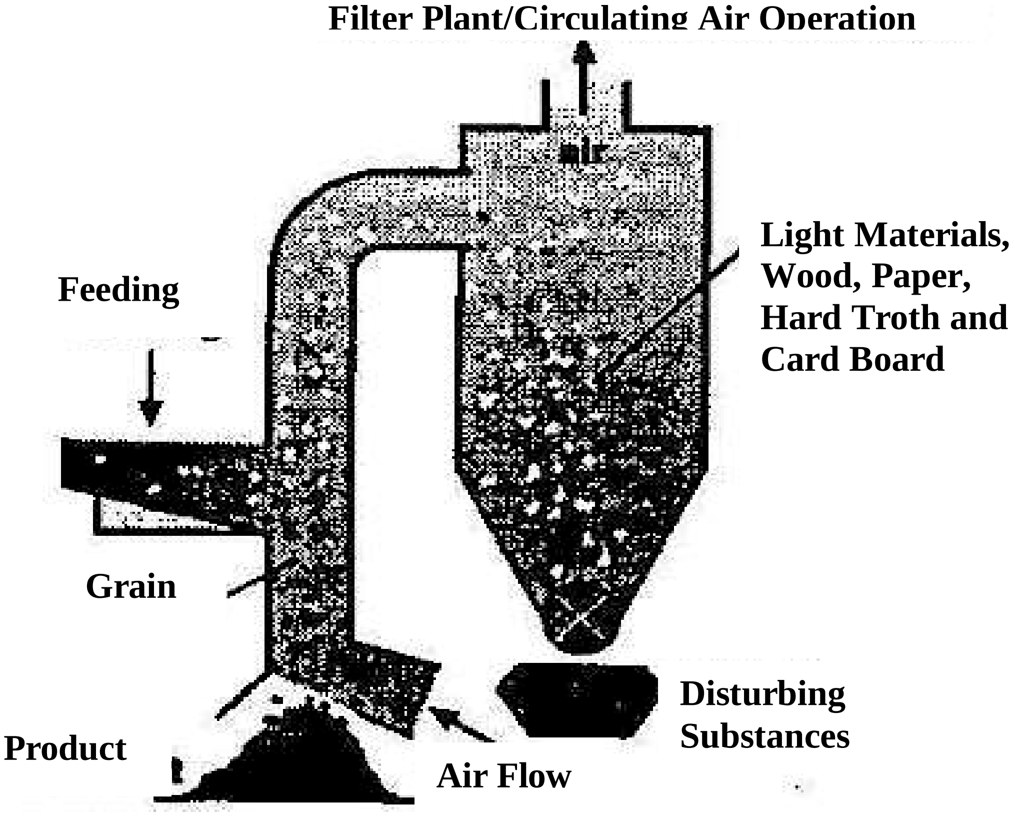
Source: Kohler and Kurkowski, 2000

Figure 2.2 Stationary Recycling Concrete Plant.

The next step involves a repetitive segregation of the resulting ferrous scrap followed by a fractional sieving and separation of light substances by air classifiers. The use of this technique allows the production of well-qualified close size fraction granulate mixtures and high quality products that can be assigned as recycling materials. The output quality can be guaranteed by a systematic and rigorous monitoring, as well as an intensive sampling and testing of the material characteristics (including environmental properties), which should be stricter than the quality control applied to natural mineral substances (Kohler and Kurkowski, 2000).

2.4 Dry and Wet Process

Conventional dry processing of recycling materials uses the air classifier (Figure 2.3) as its main component. The classification has to be done using relatively close size fractions of material in order to adjust the air speed. In this manner, the disturbing substances with slight bulk density and special particle shapes can be safely separated from the heavy mineral component. By reducing the air speed in the classifier shown in Figure 2.3, the light substances can be separated and discharged from the process. These residues are usually brought to landfills or incineration/energetic treatment plants.

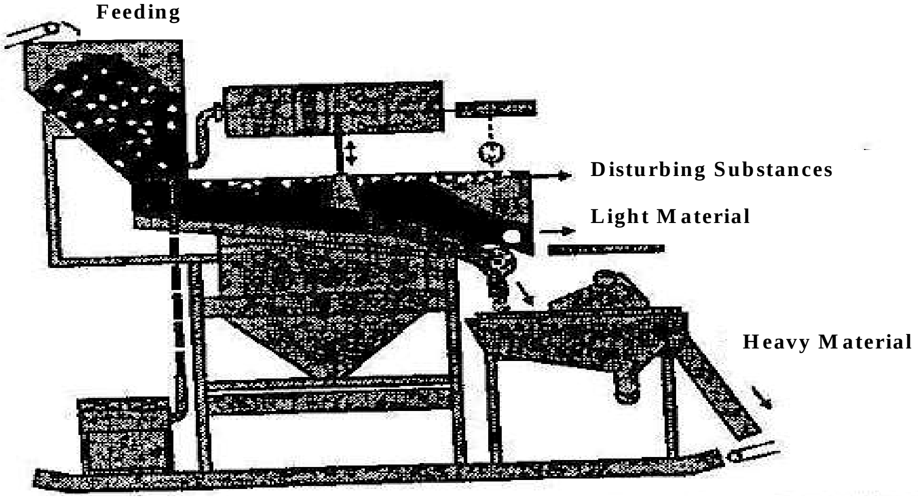


Source: Kohler and Kurkowski, 2000

Figure 2.3 Air Classifier.

Wet processing techniques become increasingly important when there is a high demand for concrete aggregates or raw materials for the production of masonry. Wet processing can be used in the production of concrete aggregates from mixed construction and demolition (C&D) waste, particularly concrete and masonry in order to achieve quality characteristics. This method provides a dust-proof surface that makes possible the separation of materials with a density lower than 124.8lb/ft^3 (2 g/cm$^{3)}$. Currently the Jig Technique (Figure 2.4) is the only method that can be applied to reach the separation of materials using wet processing (Kohler and Kurkowski, 2000).

Main factors influencing the efficiency of separation by Jig are the density differences in material mixture; bulk parts presented in the different density fractions, and particle shape.



Source: Kohler and Kurkowski, 2000

Figure 2.4 Scheme of a Jig with Star Wheel Extractor

2.5 Bulk Densities

The main components of heterogeneous recycling building materials are categorized according to Table 2.1.

Table 2.1 Bulk Densities of Heterogeneous Recycling Building Material Mixtures.

Bulk Density of the Main Components of Heterogeneous RC Building Material Mixtures	
Natural Rock	156-187 lb/ft^3 (2.5 – 3.0 g/cm^3)
Gravel	162-168 lb/ft^3 (2.6 – 2.7 g/cm^3)
Concrete	137-156 lb/ft^3 (2.2 – 2.5 g/cm^3)
Mortar	137-150 lb/ft^3 (2.2 – 2.4 g/cm^3)
Brick	112-150 lb/ft^3 (1.8 – 2.4 g/cm^3)
Lightweight Concrete	75-112 lb/ft^3 (1.2 – 1.8 g/cm^3)
Pumice	62.4-87 lb/ft^3 (1.0 – 1.4 g/cm^3)
Plastics	62.4-87 lb/ft^3 (1.0 – 1.4 g/cm^3)
Other disturbing substances	<62.4 lb/ft^3 (< 1.0 g/cm^3)

Source: Optimizing the Use of RCA, (Kohler and Kurkowski, 2000)

2.6 RCA Properties

Numerous tests have been carried out to determine the properties of recycled aggregates derived from waste concrete. The objective of the majority of these tests was to assess the suitability of this material as aggregate for concrete as stipulated by standards included in the ASTM C33, and more recently to verify the acceptability of RCA as base course for pavements.

As any natural concrete aggregate, RCA must fulfill several requirements before being used in major construction projects. For instance, recycled concrete aggregate has to be strong enough to be used in a concrete mixture, it must be able to gain an adequate strength, and it has to possess good dimensional stability, shape and grading to provide an acceptable workability. Furthermore, RCA must be inert when mixed with cement or reinforcement and be free of potential harmful impurities that could affect the environment.

Because properties of recycled aggregates differ from those of virgin aggregates (VA) in several aspects, their use in construction would depend on the nature of the project. These properties include physical, mechanical, and chemical characteristics that would greatly depend on the origin and processing of the RCA. For instance, RCA particles typically have a coarser and more angular shape than natural aggregates as a result of the crushing operations. RCA has a varying particle size distribution, depending on the crusher settings, and generally a lower density than virgin aggregates.

One of the most distinctive features of recycled aggregates is that they currently have attached mortar and cement paste on the surface of the original gravels. The percentage of this mortar attachment depends on the degree of crushing and the properties of the original concrete. The attached mortar alters some properties of the aggregates. In effect, it provides them with a lighter weight, higher water absorption, poorer bonding capacity, and lower abrasion resistance (Chan, 2001).

Another major attribute of recycled aggregates is the presence of contaminants. These substances are present in recycled aggregates from the original demolition debris and get passed on to the aggregates through the recycle process. These contaminants include clay balls, bitumen chunks, gypsum from drywall, bricks, organic material such as wood, glass, steel pieces, and other metals. Contaminants generally pose adverse effects on the mechanical properties and the durability of concrete when mixed with recycled aggregates. Therefore, a great deal of work has been done to find ways of reducing the content of these materials in the stream of waste concrete in order to mitigate their effects, and to find uses where their harmful effects can be acceptable.

The mechanical properties of concretes prepared with recycled aggregates will always differ from those made with virgin aggregates. For example, the compressive strength of RCA has reported values in the range of 0-40% lower than those of comparable concretes containing virgin aggregates (Chan, 2001). Other significant properties such as the tensile and shear strengths, and modulus of elasticity of RCA concrete have also shown lower values, while creep and shrinkage have exhibited higher numbers. The actual percent difference in each of the above properties depends on a number of factors like the fraction of total aggregates recycled, the characteristics of the original concrete, the nature and level of contaminants present, the amount of fines, and the quantity of attached mortar, etc. Therefore, the latest investigations have been aimed to determine the "optimum" combination of these factors that will economically produce a recycled concrete aggregate.

The factors previously mentioned also affect the durability of concretes containing recycled aggregates. However, the presence of contaminants is the factor that produces the most significant effect over the RCA. Foreign substances can reduce the serviceability of the concrete due to the harmful reactions they can produce. The existence of significant levels of gypsum from drywalls, for example, can cause expansive reactions that promote cracking in concrete. Another important factor that affects the durability of the concrete is the extent to which the original material has undergone harmful reactions. These reactions have the potential to continue in the new concrete if the old concrete was recycled as aggregate for new mixes (Chan, 2001). Furthermore, the permeability and water absorption of recycled aggregate will increase, and the durability of the concrete will be affected due to the attached mortar in the RCA.

Previous studies have also shown similar conclusions about RCA properties. Kobasshi and Kawano (1988) conducted tests on crushed concrete samples of different strengths to study the properties of RCA that were obtained from different degrees of crushing refinement. In order to remove the cement paste adhered to the RCA, different levels of mechanical refinement were applied. Subsequently, the materials were tested for specific gravity, absorption, soundness, abrasion loss, bulk density, solid volume percentage, and fineness modulus. The results showed that the properties of concrete made from RCA were inferior to the properties of concrete made from virgin aggregates. The study also determined that high amounts of cement paste adhered to the stone produced a poor quality of concrete. However, the research revealed that a more extensive refinement could improve the properties of RCA. At some point, the properties of a highly refined RCA obtained from weak concrete were superior to those from high strength concrete because the cement paste in weak concrete was easier to remove from aggregates than the cement paste attached to high strength concrete. Kobasshi and Kawano also concluded that the compressive strength of RCA concrete was lower than VA concrete, although both used the same water/cement ratio.

Kashino and Takahashi (1988) reported that the methods used to design, manufacture, place, and cure natural aggregate concrete can be also applied to recycled aggregate concrete. They further drew the following conclusions: 1) the strength characteristics of RCA concrete obtained in the laboratory were reflected in the actual structure, 2) up to 30% of RCA in concrete had little effect on compressive strength, 3) larger particles of RCA had less percentage of adhering cement paste as compared to smaller particles, and 4) RCA concrete required slightly more air-entraining agent to maintain a particular requirement.

A study conducted by Sri Ravindrarajah and Tam (1988) found that a decrease in the size of RCA produced an increase in the volume content of mortar attached to aggregates, which ranged from 20% for the 0.63-1.25 in. (16-32 mm) in size to 60% for the 0.16-0.31 in. (4-8 mm size) in size. They also found that the water absorption of RCA increased with the decrease in the aggregate size. The mechanical properties analysis made by Sri Ravindrarajah and Tam revealed that RCA particles were more angular than VA, having higher abrasion value, and less abrasion resistance with reduction in aggregate size than VA. In addition, their tests on concrete showed that RCA concrete required about 10% more water than VA concrete for a similar workability, 25% less compressive strength, and a 30% reduction in modulus of elasticity. The conclusions of their study stated that a reduction of the water-cement ratio, addition of pozzolan, and blending of RCA with VA could improve the qualities of RCA concrete. The study also indicated that a drying shrinkage could be reduced by a prolonged initial moist-curing period, and the RCA absorption capacity was not substantially influenced by the quality of the original concrete.

Kibert (1994) recently reported that there were no National specifications in the U.S. for the use of RCA concrete in road construction. Thus, RCA properties were based on the existing specifications of natural aggregates. According to Kibert's report; the shape of RCA particles was more irregular and the surface texture was coarser than VA. Moreover, the report stated that RCA exhibited higher water absorption (5% to 8%), less density, similar durability under freeze-thaw conditions, lower compressive strength (64% - 100%), lower modulus of elasticity (60% - 100%), and less flexural strength (80% - 100%) as compared to VA.

2.6.1 Physical Properties

Table 2.2 shows the results of a research study conducted by Chini and Kuo (1998). These test results reveal some basic physical properties of RCA along with FDOT specifications of VA (RP #1041) and sand (RP # 3156) on specific gravity, water absorption, unit weight, LA abrasion, and void ratio. As seen in the table, the values of RCA properties are very close to VA specifications and RCA is considered a favorable material to use. In their study, the gradation of RCA sample used #57 as coarse aggregate. The FDOT specification and limits on #57 virgin aggregate are given in Table 2.3. By comparing those values, the sample of RCA used in the study was considered to have an acceptable gradation range for the state specification #57 on coarse aggregate. It is apparent from the table that the RCA sample possessed smaller particles than VA #57 specifications. This may be the reason that the RCA sample presented in Table 2.2 had higher water absorption, LA abrasion, and higher compacted unit weight than VA.

Table 2.2 Properties of RCA, VA, and Sand

PARAMETER	AGREGGATE TYPE		
	RCA	VA (RP # 1041)	SAND (RP # 3156)
Specific Gravity (SSD)	2.43	2.42	2.64
Water Absorption (SSD), %	4.36	4.1	0.6
Unit Weight, lb/ft^3	88.2	84.2	----
LA Abrasion, %	33.9	32.6	----
Void Ratio, %	41.9	----	----

Source: Guidelines and Specifications for the Use of Reclaimed Aggregates in Pavements (Chini & Kuo, 1998).

Table 2.3 Gradation of RCA, VA and Sand (% passing).

Sieve Size, (mm)	**Sand**		**Coarse Aggregate, #57**		
	Sample	**Limits**	**RCA**	**VA**	**Limits**
37.5	----	----	100	100	100
25	----	----	97.6	100	95-100
12.5	----	----	46.4	42	25-60
4.75	100	95-100	4.8	3	0-10
2.36	100	80-100	4.2	1	0-5
1.18	95	50-85	----	----	----
0.6	62	25-60	----	----	----
0.3	18	5-30	----	----	----
0.15	1	0-10	----	----	----
0.075	0	0-4	----	----	----

Source: Guidelines and Specifications for the Use of Reclaimed Aggregates in Pavements (Chini & Kuo, 1998).

2.6.2 Chemical Properties

RCA alkalinity is considerably affected by its cement paste component. Cement paste consists of a series of calcium-aluminum-silicate compounds, including the highly alkaline calcium hydroxide that makes the RCA-water mixtures frequently surpass a pH of 11. Moreover, substances such as chloride ions from the application of deicing salts to roadway surfaces and sulfates from contact with sulfate-rich soils may also contaminate the RCA. Chloride ions can cause steel corrosion, while sulfate reactions may lead to an expansive disintegration of cement paste. RCA may also contain aggregate susceptible to alkali-silica reactions (ASR) that could cause expansion and cracking if it is mixed in concrete. Also, RCA with high alkaline content (pH greater than 11) can cause corrosion of aluminum or galvanized steel pipes when it is directly contacted with water (Federal Highway Administration, 1997).

2.6.3 Mechanical Properties

Processed RCA with particles greater than 4.75 mm in size (No. 4 sieve size), have provided fairly good mechanical properties including high abrasion resistance, good soundness characteristics, and considerably high bearing strength. Table 2.4 shows typical mechanical properties of reclaimed concrete. From the table, the values of Los Angeles Abrasion loss are somewhat higher than those of high-quality conventional aggregates, while Magnesium sulfate soundness and California Bearing Ratio (CBR) values are comparable to conventional aggregates (Federal Highway Administration, 1997).

Table 2.4 Typical Mechanical Properties of Reclaimed Concrete Material

Property	Value
Los Angeles Abrasion Loss (ASTM C131), (%) - Coarse particles	20-45
Magnesium Sulfate Soundness Loss ASTM C88), (%) - Coarse particles - Fine particles	4 or less Less than 9
California Bearing Ratio (CBR), (%)*	94 to 148
*Typical CBR value for crushed limestone is 100 percent	

Source: (Federal Highway Administration, 1997).

2.7 Performance of RCA as Base or Sub-base for Pavements

In the study about the use of reclaimed aggregates in pavement, Chini and Kuo (1998) describe in detail the aggregate properties that influence the functions of pavement bases courses. These properties include aggregate stability, particle size distribution, permeability, plastic index, Limerock Bearing Ratio, particle shape, soundness, sodium sulfate test, abrasion test, and compaction.

Snyder and Bruinsma (1996) have carried out research since the mid 1980's in which they have studied the effects of unbound crushed concrete bases on PCC pavement drainage. The main conclusions of their investigations are:

- All recycled aggregates were able to produce various amounts of precipitate and their precipitate potential is directly related to the amount of freshly exposed cement paste surface. However, the grading or blending of selected recycled aggregates with virgin aggregates can significantly reduce the precipitate potential.
- Insoluble non-carbonate-based residues made up a major portion of materials found around pavement drainage systems. Washing the RCA before using it as a base or sub-base appears to reduce the potential for accumulation of crusher dust and other fines.
- Precipitates and insoluble residue accumulations can produce significant reductions in the permeability of typical drainage filter fabrics due to a high initial release of fines.

- Within the first few years the effluent from RCA bases were slightly more alkaline and then dropped to average. The increased pH, however, was not enough to cause any major environmental impact because it was quickly diluted or neutralized by the larger influx of surface runoff.

Two years later, Liu, Scarpas, Blaauwendraad, and Genske (1998) performed parametric analyses of unreinforced pavements, which consisted of determining the load bearing capacity and the expected life span of different base materials such as natural aggregate, crushed concrete, and crushed masonry. They found that because of their increasing flexibility, pavements with bases consisting of recycled aggregates demonstrated a higher permeability (*K)* value. According to Liu et al. with known value of k, the service life of the pavements can be computed by means of Paris Law.

The Federal Highway Administration FHWA (2000) conducted a six-year study about RCA materials processed from uncontrolled stockpiles to be used as a granular subbase or base in Long Island, New York. The results as shown in Table 2.5 indicated that physical properties such as magnesium sulfate soundness, Los Angeles Abrasion, density, and CBR of RCA were very consistent and fell within predictable ranges.

The study also stated that RCA properly processed and tested for appropriate specification compliance had been widely used and generally demonstrated satisfactory performance in granular base applications.

Table 2.5 Six-year Study of RCA from Uncontrolled Stockpiles in Long Island, NY.

Physical Property	Test Results		Tests performed
	Mean	Std. Dev.	
Magnesium Sulfate Soundness (%)	3.8	1.3	107
Los Angeles Abrasion (%)	36.5	3.6	112
Dry Density (lb/ft^2)	129.0	2.6	143
CBR (%)	148.0	28.7	157

Source: The Federal Highway Administration, 2000

According to the FHWA (2000), twenty states in the U.S. are currently using RCA in pavement construction. These states are Arizona, California, Colorado, Florida, Indiana, Iowa, Louisiana, Maryland, Massachusetts, Minnesota, Missouri, Nebraska, New Jersey, New York, North Dakota, Ohio, Pennsylvania, Rhode Island, South Carolina, and Texas. The FHWA report implies that the positive features shown by RCA used as a granular base in pavement were due to the material's ability to stabilize wet, soft, and underlying soils at early construction stages, as well as having good durability, bearing strength, and drainability characteristics. However, a number of agencies have recently reported evidence that some improperly processed or unsuitable RCA can adversely affect pavement subdrainage systems and pavement performance because of Tufa-like precipitates, as discussed previously.

Although many studies on RCA as base course have been conducted in the United States and other countries, there are still some issues that need further investigation such as, tufa formation of RCA in granular base, long-term performance and life cycle cost data for concrete made with processed RCA to assess its: 1) durability, 2) performance, 3) expected service life, and 4) the effect of impurities as wood asphalt, and earth on concrete performance (Federal Highway Administration, 1997).

2.8 Guidelines and Specifications

In a research report, Chini and Kuo (1998) presented a survey of State Departments of Transportation regarding the current use of recycled aggregates for pavement construction in the U.S. and Puerto Rico. A total of 45 replies were received from 51 surveys prepared by The Department of Transportation's Materials Engineers.

Results of the survey indicated that state agencies of 26 states allowed the use of reclaimed Portland cement concrete as a base course aggregate while four states allowed the use of RCA as a sub-base aggregate. However, only 15 of the 28 state agencies that use RCA in base and subbase applications have standard specification guidelines for recycled aggregates. Two states use the same specifications for natural and recycled aggregates, and evaluate the recycled materials on a project-by-project basis while some states specify more requirements than others. For example, Florida Specifications only require a Los Angeles Abrasion Loss value lower than 50%, Michigan Specifications only allow using RCA on roads with an ADT less than 250 on concrete pavement, while Pennsylvania Specifications require:

- Gradation Chart
- Max. % Abrasion = 40
- Max. % Thin and elongated pieces = 5
- Max. % Material finer than # 200 sieve = 10

- Min. % Crushed fragments = 55
- Min. Compaction dry unit weight = 70 lb/ft^3
- Max. % Deleterious shale = 2
- Max. % Clay lumps = 0.25
- Max. Friable particles (excluding shale) = 1.0
- Max. % Coal or coke = 1
- Max. % Total of deleterious shale, clay lumps, friable particles, and coal or coke = 2
- Los Angeles Abrasion Loss < 55% by weight

The Chini and Kuo report (1998) also presented a review of international standards from Australia, Belgium, Canada, France, Japan, Netherlands, Spain, and the United Kingdom for their use of RCA.

2.8.1 Australia

Australian VicRoad specifications 820 Q requires:

- Upper sub-bases shall have a maximum plasticity index of 10 and lower sub-bases 20
- Abrasion loss as measured by Los Angeles test shall be less than 35% for upper sub-bases and 40% for the lower sub-bases
- The amount of high-density materials present as brick and asphalt shall be less than 3% for upper sub-bases and 5% for the lower Sub-bases.

2.8.2 Belgium

According to Vyncke and Rousseau (1994), two types of RCA (GBSB-I and GBSB –II) were allowed to use in Belgium. The quality requirements of RCA is presented in Table 2.6

Table 2.6 Quality Requirements of Concrete Aggregate

Property	GBSB-I	GBSB-II
Dry density (kg/m^3)*	> 1600	> 2100
Water absorption	< 18	< 9
Content of material with a density < 2100 kg/m^3 (%)	-	< 10
Content of material with a density < 1600 kg/m^3 (%)	< 10	< 1
Content of material with a density < 1000 kg/m^3 (%)	< 1	< 0.5
Foreign materials (%)	1	
Organic material (%)	< 0.5	
Chloride content (%)	< 0.06	
Sulphate content (%)	< 1	

1 kg/m^3 = 1.68556 lb/yd^3. Source: Vyncke and Rousseau, 1994

2.8.3 Canada

In Canada, RCA is primarily used as a granular base material. The current Canadian Ministry of Transportation specifications allow the use of up to 100% of recycled concrete in granular A (Senior, 1992). The specifications in Granular A are Canada's most stringent requirement for base aggregates and must be met by both natural and recycled concrete aggregates. The gradation and physical specifications in Granular A are shown in Tables 2.7 and 2.8.

Table 2.7 Granular A Gradations

Sieve (mm)	Percent Passing
26.5	100
19.0	90-100
16.0	
13.2	65-90
9.5	50-73
4.75	35-55
2.36	
1.18	15-40
0.300	5-22
0.075	2-8

Source: Guidelines and Specifications for The Use of Reclaimed Aggregates in Pavement (Chini & Kuo, 1998)

Table 2.8 Physical Requirements for Granular A

Ministry of Transportation Test[1]	Test Number	Requirement
LA Abrasion (max)	LS-603	60%
%Crushed (min)	LS-607	50%
Petrographic Number, (gran, max)	LS-609	200
Plasticity Index[2]	LS-704	0

Source: Guidelines and Specifications for The Use of Reclaimed Aggregates in Pavement (Chini & Kuo, 1998)

1. Ministry of Transportation, 1989.
2. Material Passing the 0.075 mm sieve (fines) shall be non-plastic; i.e., has a plasticity index of 0.

2.8.4 France

The use of recycled materials in France is limited to roadwork and land filling (90% a aggregates, 10% with binders). After initial screening to 40 mm, the materials are crushed and screened into these aggregate sizes:

- Sand 0/6 mm
- Gravel 6/25 mm
- Stone 25/40 mm

The French selection criteria exclude materials obtained from building demolition and construction site waste due to the presence of gypsum.

2.8.5 Japan

The Japanese quality requirements for recycled concrete bases provided acceptable limits for abrasion, bearing strength and plasticity. Los Angeles abrasion test for the percent weight loss of RCA should be less than 50%. Other specified quality requirements are shown in Table 2.9.

Table 2.9 Quality of Recycled Crusher-Run Used for Road Base

	Materials	**Corrected CBR %**	**Plasticity Index**
Simple Pavement	Recycled Crusher-Run	10 over	9 under
Asphalt Pavement	Recycled Crusher-Run	20 over	6 under
Cement Concrete Pavement	Recycled Crusher-Run	20 over	6 under

Source: Guidelines and Specifications for The Use of Reclaimed Aggregates in Pavement (Chini & Kuo, 1998)

2.8.6 Netherlands

Holland's Government developed a regulation in 1984 named the CUR-VB Recommendation 4, which covers the control and acceptance testing of crushed concrete. The CUR-VB Recommendation 4 states

> " The principal constituent, the crushed concrete aggregate, must be at least 95% of the total. Not more than 5% may consist of secondary materials such as clay-bricks, sand-lime building bricks, lightweight concrete, foamed concrete, ceramic materials and masonry-mortar, with the definite exclusion of gypsum and gypsum containing materials. Not

more than 1% of the crushed concrete may consist of non-stone-like constituents such as wood, paper, glass, textiles, bituminous materials, etc.”

2.8.7 United Kingdom

The United Kingdom’s Specification for Highway Works allows the use of RCA in concrete pavement providing that RCA fulfills the quality and grading provisions of B882. The B882 recommendation of quality tests include:

- Strength and flakiness
- Chloride content (due to deicing salts)
- Sulphate content (SO_3)
- Alkali-silica reaction
- Cleanliness, hardness, and durability
- Magnesium Sulphate soundness mass loss

Table 2.10 shows the quality requirements of RCA.

Table 2.10 Quality Requirements of Concrete Aggregate

AGGREGATE PROPERTY	LIMITING VALUE (%)
Flack particles	40
Sulphate, SO_3	4*
Drying shrinkage	0.075
Soundness test (Magnesium Sulphate)	25
Water absorption	2

*(%) Percentage with respect to cement. Source: Collins, 1988 Source: Collins, 1988

In summary, research from the afore mentioned countries concluded that the quality of RCA depends on the production process, which includes the type of crusher and the number of crushing cycles used. The investigations observed that:

1. The multiple crushing of aggregates reduced the amount of mortar adhered to particles, resulting in improved water absorption and stability properties of RCA.
2. High strength original concrete may not always produce high quality RCA. When multiple crushing refines the aggregates, mortar adhered to aggregates from weak original concrete easily falls off resulting in better quality RCA, which is low water absorption and high density.
3. The mortar attached to stone particles increased trapped air, thus entrained air content of RCA concrete resulted to be higher than VA concrete.
4. Water absorption, stability (chemical and physical), and harmful compositions, such as residual soils, residue powder from crushing process and excessive chloride can be reduced by avoiding recycled fine aggregates.

CHAPTER 3

SURVEY OF RECYCLED CONCRETE PLANTS IN FLORIDA

In order to determine the current status of concrete recycling in Florida, a survey was developed and sent to twenty companies known to recycle Portland Cement Concrete. Surveyed companies were assessed to determine each plant's production, the type of material produced and commonly used. The names of these companies were sought from previous surveys and from referrals. A total of fifteen companies responded to the survey (a 75% of response rate). The questions in the survey are listed following.

3.1 Questionnaire

Question 1a: Is your operation fixed or mobile?

Six of the fifteen companies surveyed have mobile crushers. The mobile crushers are operated on the site where the deteriorated concrete structures are demolished. The use of mobile crushers may be associated with expensive transportation and labor costs. Table 3.1 shows the type of operation used by the surveyed companies.

Table 3.1 Type of Operation

Fixed Location Operation	5
Mobile Operation	6
Both Fixed and Mobile	4

Question 1b: What is your daily production of recycled concrete aggregate?

There was a considerable range for the daily production of recycled concrete. The biggest producer claims to produce more than 2000 US tons a day, while the smallest producer produces less than 100 US tons a day (see Table 3.2). The total production of recycled concrete from all companies surveyed is about 15,000 tons/day.

Table 3.2 Daily production of recycled concrete aggregate

0-100 tons/day	1
100-200 tons/day	1
200-500 tons/day	4
500-1000 tons/day	3
1000-1500 tons/day*	2
1500-2000 tons/day	1
More than 2000 tons/day	3

Question 1c: What type of crusher do you use?

The most common crusher used was identified as an impact crusher. Some companies use a combination of both jaw and impact crushers in their operations (see Table 3.3).

Table 3.3 Type of crusher

Jaw Crusher	3
Impact Crusher	9
Both	3

Question 2a: What are your sources of material?

The most common sources of concrete for recycling were from:

- Curbs
- Slabs

- Sidewalks
- Concrete Yards
- Old Roads, Highways, & Bridges
- Construction & Demolition Debris

Question 2b: What type of recycled material do you produce?

The products are:

- Fill Dirt
- Screening ½” Minus
- No. 89 FDOT [(0.37” to 0.0465”) (9.5 to 1.18 mm)] coarse aggregate
- No. 57 FDOT [(1” to 0.187”) (25 to 4.75 mm)] coarse aggregate
- No. 4 FDOT [(0.75” to 1.48”) (19 to 37.5 mm)] coarse aggregate
- No. 5 FDOT [(0.5” to 1”) (12.5 to 25 mm)] coarse aggregate
- Base Material [(3/8”, 1 ½”, 3” minus) (9.5 mm, 38.1 mm, 76.2 mm)]
- Rip Rap, and Rubble Concrete

Question 2c: Who are your most common clients and for what applications is your product being used?

The most common clients to acquire recycled concrete aggregates are contractors and private entities. According to the surveys the products are used for:

- Pipe Bedding
- Fill
- Erosion Control

- Base and Subbase Courses (Parking Lots, private driveways, widening of shoulders & roads)
- Building Blocks
- Asphalt Mixture
- Septic Tanks & Drain fields

Question 3a: How dose the cost of recycled concrete aggregate compare to the cost of natural aggregate in your area?

The responses are listed in Table 3.4. Ten companies (67%) reported that recycled concrete aggregate was less expensive than natural aggregate (NA). This price reduction may be attributed to disposal fees that concrete recycling companies are charging for receiving concrete waste material. Otherwise the waste material would end up in landfills at a much higher disposal cost.

Table 3.4 Cost of RCA Comparing to Cost of Natural Aggregate

RCA is less expensive	10
RCA is more expensive	2
They are the same price	3

The geographical location of the recycling plant also plays a role in the price of recycled concrete aggregate. In South Florida, virgin aggregate is less expensive than recycled aggregate due to its availability. However, in North Florida, the hauling costs are higher, thus virgin aggregate is more expensive than recycled aggregate. Figure 3.1 shows the RCA cost comparison between the Florida Districts.

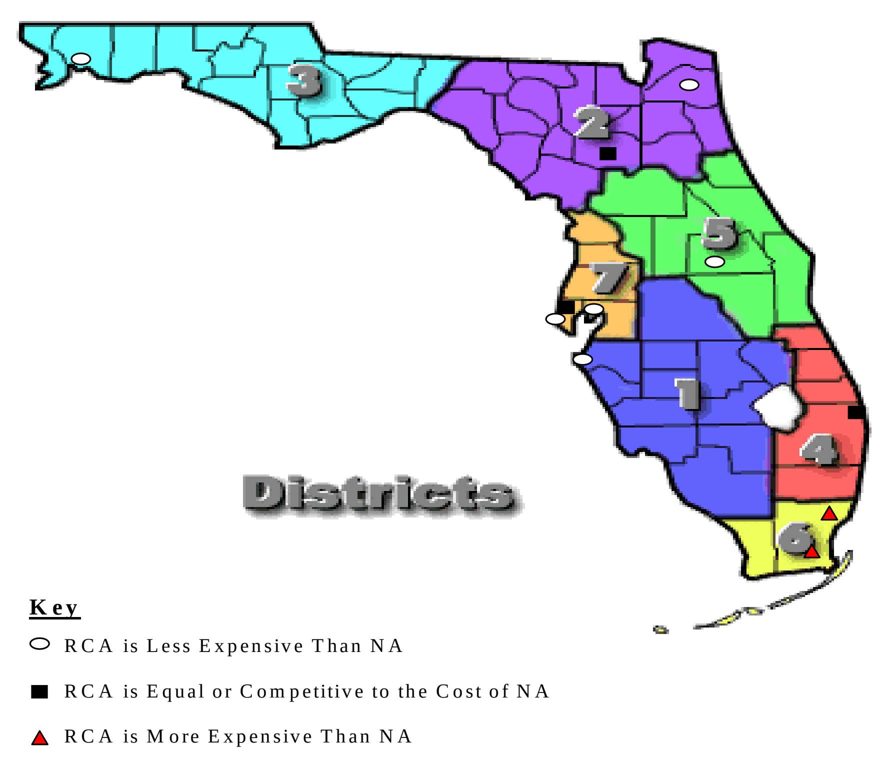


Figure 3.1 RCA and NA Cost Comparison Map in Florida

Question 3b. Does your product meet any agencies' (city, county, state) specifications? If yes, please specify.

Eleven of the companies surveyed responded that their products meet local municipal specifications (city, county, state district). The Florida State Health Department under chapter 10-D-6 has approved the use of recycled concrete aggregate in septic tank drain fields. RCA has been approved as an equal to shell rock and may be used as parking lot base in Palm Beach County. In Pinellas County RCA has even been used as a road base with special permits.

Question 3c: have independent testing laboratories tested your product? If yes, is it possible to include a copy of the test results?

The Table 3.5 shows the responses for the Question 3C

Table 3.5 Laboratory Test of RCA.

Yes	11
No	3
No response	1

Question 4: We are having trouble locating concrete aggregates recycling plants. Do you know the names or contact persons of any other companies that produce recycled concrete aggregates in Florida?

The state of Florida does not require any special license or permit to operate a concrete recycling plant in Florida. Nor are there any associations within Florida for concrete recycling plants. This along with the mobile nature of some of these companies makes it difficult to locate concrete recycling companies. This question aimed to obtain additional references on concrete recycling companies.

Question 5: Do you have any additional comments?

Additional comments made by some respondents were:

- “I welcome this survey wholeheartedly. We produce a great material that definitely has a place in D.O.T. Standards. We have been manufacturing recycled concrete for approximately ten years.”
- “We have about 12 years experience in recycled concrete. We believe as base rock, it should be equal to lime rock.”
- “Because recycled concrete base has a higher LBR and less fines, it can be worked through a rain storm that would shut down work with a limerock base. The more water is better. Because of freight cost for natural

aggregate in this area, we not only reduce dumping in our landfills, but provide the aggregate user with a lower cost material that in some uses is better than the higher cost natural aggregate. I offer my customers the free service of making them a mix design using my aggregate for their fresh concrete use."

- "LBR test results indicate that the recycled materials tested should provide adequate strength when placed as roadway base material. LBR values obtained on samples from the recycled sites are generally equal to or greater than values of limerock samples that we have encountered in the past. Visual inspection also indicates that the recycled material should be less vulnerable to water influences than limerock, which will tend to lead to a more durable product."

A total of fifteen companies representing 75% those surveyed (population) responded. A summary exhibiting the perception of the population regarding these issues is shown in Table 3.6.

Table 3.6. Summary of Survey to Recycled Concrete Plants in Florida

Issue	**Aspects with highest number of answers**	**Number of positive responses with respect the total population (15)**	**Percentage (%) of positive responses with respect the total (15)**
Type of Operation	Mobile Operation	6	40
RCA Daily Production	200-500 tons/day	4	26.67
Type of Crusher Used	Impact Crusher	9	60
Sources of Material	Pipe bedding, fill, erosion control, base and subbase courses, buildings blocks, asphalt mixture, and septic tanks & drain fields	No data available	
Common Clients	Contractors and Private Entities	No data available	
Cost of RCA compared with Virgin Aggregates	RCA is less expensive	10	66.67
Compliant with existing agencies specifications	Products meet local Municipal specifications	11	73.33
Product Quality Verification by Independent Laboratories	Yes	11	73.33
Troubles found locating RCA producer plants	Difficult due to the mobile nature of some of the companies	No data available	
Additional Comments	• RCA is a great material • RCA can equal limerock • RCA is more workable than limerock in raining conditions • RCA is less expensive and for some uses is better than more expensive natural aggregates • RCA provides adequate results when placed as roadway base material. LBR values are equal or higher than values obtained from limerock samples. Visual inspection indicates that RCA presents lower vulnerability to water and more durability than limerock.		

3.2 Sampling

In order to adequately evaluate the quality of RCA in the state of Florida, a concrete recycling plant from each of the seven Florida Districts was scheduled to sample once a month for six months. Priority of plant selection was given to those recyclers with a fixed operation, the largest production, and the longest experience in the field. A recycling plant was selected in each district, except for District 3 where there was no record of recyclers. There were two recycling plants located in District 4 and one in District 6, however, due to budget constraints and site remoteness, the RCA materials were not initially scheduled for sampling. Through the cooperation of the FDOT and PSI consultant, samples from both districts were later collected for three months.

A two-man crew collected RCA materials from Districts 1,2,5, and 7 from the University of Central Florida (UCF) and University of Florida (UF) following the Florida Department of Transportation (FDOT) sampling procedures (FM 1-T 002). Upon the completion of sampling, the materials were immediately distributed to the laboratories at FDOT State Materials Office in Gainesville, FDOT District 5 in Deland and the UCF test facility in Orlando.

CHAPTER 4

LABORATORY TEST PROCEDURES AND RESULTS

Recycled concrete materials can be used as either aggregates for concrete mixtures or base course for flexible and rigid pavements. However, thorough material characterizations must be determined before the materials can be used successfully in major construction projects.

This chapter will describe the laboratory test methods and discuss the results pertaining to the RCA collected from various sources around the State. Statistical approaches such as the arithmetic mean, standard deviation, and percent of confidence are applied to the test data in order to establish the reasonable standard value. The materials tested in this study were basically demolished concrete pavement with little portion of demolished buildings collected from recycling plants operating at Districts 1 through 7 in Central and South Florida.

The laboratory tests conducted in this project included: aggregate gradation, limerock bearing ratio (LBR), LA abrasion, soundness, sand equivalent, heavy metals, modified proctor compaction, hydraulic conductivity and impurity contents. In addition, the asphalt pavement test sections made with the two RCA and one limerock base courses were tested at the UCF Circular Accelerated Test Track (UCF-CATT) for evaluation of fatigue and rutting distresses. All laboratory test methods were based on the FDOT testing specification as shown in Table 4.1.

Table 4.1 Aggregate Test Methods

TEST METHOD	FDOT (ASTM) DESIGNATION
Reducing Field Samples of Aggregate to Testing Size	FM 1-T 248
Sampling Coarse and Fine Aggregate Test	FM 1-T 002
Sieve Analysis of Fine and Coarse Aggregate Test	FM 1-T 027 (C-136)
Florida LBR Test	FM 5 - 515
LA Abrasion (Small-sized Coarse Aggregate) Test	FM 1-T 096 (C-131)
Soundness	AASHTO T- 104
Sand Equivalent Test	AASHTO T- 176 - 86
Heavy Metal	EPA - 96
Compaction Test	FM 5 - 521
Specific Gravity Test	FM 1 T - 085
Hydraulic Conductivity Test	FM 5 – 513
Impurities Analysis	FM 1 T - 194

Source: Guidelines and Specifications for the Use of Reclaimed Aggregates in Pavements, 1998
FDOT Standard Specifications for Road and Bridge Construction, 1999

4.1 Particle Size Distribution (Gradation)

The most significant contributor to a base course's internal friction and shear strength is the particle size distribution, particularly the portion of very fine (diameter < 75 μm) to coarse fraction. To determine the particle size distribution, a sieve analysis was performed on dry samples. A consultant from Universal Engineering was contracted by the FDOT Materials Office to perform the sieve analysis. The gradation of the RCA samples was compared to those of natural aggregate due to the more stringent requirements on recycled materials. The current FDOT specifications for graded aggregate size distribution are given in FDOT Specifications Section 204. The results of gradation from all samples collected at Districts 1 through 7 are presented in Tables 4.2 through 4.7 along with the FDOT specifications. The asterisk footnotes under the tables refer to the asterisks shown in the tables.

Table 4.2 District 1 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 1						
		December	January	February	March	April	May	Average
50 mm (2”)	100	100	100	100	100	100	100	**100.0**
37.5 mm (1½”)	95-100	100	100	100	100	100	100	**100.0**
19 mm (3/4”)	65-90	84.6	75.9	70.5	85	68	73.8	**76.3**
9.5 mm (3/8")	45-75	62.6	50.9	45.2	64.5	42.8	46.7	**52.1**
4.75 mm (#4)	35-60	47.6	38.3	34.2*	49.1	31.2*	34.7*	**39.2**
2.0 mm (#10)	25-45	35.9	29.1	26.1	36.1	23.8*	26.5	**29.6**
300 mm (#50)	5-25	13.3	12.3	11.1	11.8	10.6	11.4	**11.8**
75 mm (#200)	0-10	2.8	4	3.4	3.4	3.7	4.4	**3.6**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

Table 4.3 District 2 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 2						
		December	January	February	March	April	May	Average
50 mm (2”)	100	100	100	100	100	100	100	**100.0**
37.5 mm (1½”)	95-100	99.2	97.1	98.9	99.3	97.4	99.2	**98.5**
19 mm (3/4”)	65-90	72.7	56.6*	82.5	85.5	81	80.5	**76.5**
9.5 mm (3/8")	45-75	51.5	39.7*	53.4	65.1	58.5	54.6	**53.8**
4.75 mm (#4)	35-60	36.8	30.6*	38.1	48.5	44.5	38.5	**39.5**
2.0 mm (#10)	25-45	27	24.4*	28.9	36	34.7	28.5	**29.9**
300 mm (#50)	5-25	12.6	13.9	15.8	17.8	20.9	14.9	**16.0**
75 mm (#200)	0-10	4.7	6	3.3	4.6	2.6	3.6	**4.1**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

Table 4.4 District 4 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 4			District 4 (TSR)			Average
		July	August	September	July	August	September	
50 mm (2")	100	100	100	100	***	100	100	**100.0**
37.5 mm (1½")	95-100	97.7	97.6	100	***	100	100	**99.1**
19 mm (3/4")	65-90	73.1	75.8	85.8	***	83.3	86.3	**80.9**
9.5 mm (3/8")	45-75	51.2	54.7	68.6	***	42.3*	61.5	**55.7**
4.75 mm (#4)	35-60	37.4	42.1	51.2	***	23.7*	46	**40.1**
2.0 mm (#10)	25-45	26	30.5	30.3	***	14.5*	35.5	**27.4**
300 mm (#50)	5-25	11.9	12.5	10.8	***	4.8	13.5	**10.7**
75 mm (#200)	0-10	3.5	4.2	3.2	***	3.0	5.4	**3.9**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

Table 4.5 District 5 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 5						
		December	January	February	March	June	July	Average
50 mm (2")	100	100	100	100	100	100	100	**100.0**
37.5 mm (1½")	95-100	100	100	100	100	100	100	**100.0**
19 mm (3/4")	65-90	99.8*	99.9*	99.9*	100*	99.2*	99.2	**99.7***
9.5 mm (3/8")	45-75	72.8	82.8*	81.6*	91.7*	74.5	78.2*	**80.3***
4.75 mm (#4)	35-60	55.6	64.6*	58.3	68.7*	41.4	48.6	**56.2**
2.0 mm (#10)	25-45	44.6	50.4*	45.6*	54.5*	31.6	39	**44.3**
300 mm (#50)	5-25	16.8	20.1	19.9	25	13.5	16.4	**18.6**
75 mm (#200)	0-10	3.4	5.2	3	3.4	3.3	0	**3.1**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

Table 4.6 District 6 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 6		
		July	August	September
50 mm (2")	100	99.1*	**	**
37.5 mm (1½")	95-100	85.6*	**	**
19 mm (3/4")	65-90	49.8*	**	**
9.5 mm (3/8")	45-75	37.1*	**	**
4.75 mm (#4)	35-60	33*	**	**
2.0 mm (#10)	25-45	29.6	**	**
300 mm (#50)	5-25	19.8	**	**
75 mm (#200)	0-10	0	**	**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

Table 4.7 District 7 Gradation (Percent Passing)

Sieve Size	FDOT Sect. 204	District 7						
		December	January	February	March	April	May	Average
50 mm (2”)	100	100	100	100	100	100	100	**100.0**
37.5 mm (1½”)	95-100	100	100	100	100	98.7	100	**99.8**
19 mm (3/4”)	65-90	88.4	89.5	75.5	79.6	81.8	80.3	**82.5**
9.5 mm (3/8")	45-75	70.7	73.4	56.5	59.4	62.2	56.9	**63.2**
4.75 mm (#4)	35-60	56.7	60.2*	44	46.1	50.1	43	**50.0**
2.0 mm (#10)	25-45	45.50*****	48.3*	34.7	36.4	40.6	33.7	**39.9**
300 mm (#50)	5-25	21.6	25.6*	16	18	22	19.8	**20.5**
75 mm (#200)	0-10	4.4	5.2	3.6	4.3	4.4	3.1	**4.2**

* Does not meet FDOT Sect. 204 requirements.
** Not tested this month.
*** Sample not collected for this month.

A careful review of each table reveals that District 1 data, for the months of February, April, and May, presented some lapses in meeting the required gradation for 4.75 mm sieve. However the average gradation for this RCA appeared to comply with FDOT Section 204 standards. Samples from District 2 exhibited some anomalies and did not meet FDOT Section 204 specifications in January. The average gradation for all samples from District 2 was within the standard ranges. The average gradation of two plants in District 4 was within FDOT specifications, with exception of a few anomalies in the month of August at the TSR sample site. Several samples from District 5 did not comply with the established benchmark, thus causing the average gradations of the 19mm and 9.5mm sieves to be out of specification. Only one sample was tested for gradation from District 6. This sample failed on the percent passing sieve sizes of 50mm, 37.5mm (1½”), 19mm (3/4”), 9.5mm (3/8"), and 4.75mm (#4). A high quantity of foreign material in the District 6 samples and the dangers associated with sample handling prevented any additional gradation testing. Samples from

District 7 also demonstrated some anomalies for the month of January for not complying with three sieve sizes of 4.75mm (#4), 2.0mm (#10), and 300mm (#50). The average gradation from District 7, however, met the requirements for graded aggregate material. The average gradations listed in Tables 4.2 to 4.7 are plotted in Figure 4.1 and summarized in Table 4.8. Also included in Table 4.8 are the arithmetic average gradation, the standard deviations, 90% confidence interval, and FDOT Section 204 Specification. From the standard deviations and the confidence level, it is apparent that there were enough data to establish a 90 percent confidence interval for all recycled concrete materials collected. Figure 4.1 and Table 4.8 show that the average RCA gradation from every sieve size meets the FDOT Section 204 specification. However, at 90% intervals (min. and max.) from sieve sizes of 19 mm (3/4”), 9.5 mm (3/8"), 4.75mm (#4), and 2.0mm (#10) slightly fell out of FDOT specified materials since the standard deviations for these four sieve sizes are relatively high. As the test results show, it seems that those four sieve sizes may become more critical for recycled materials.

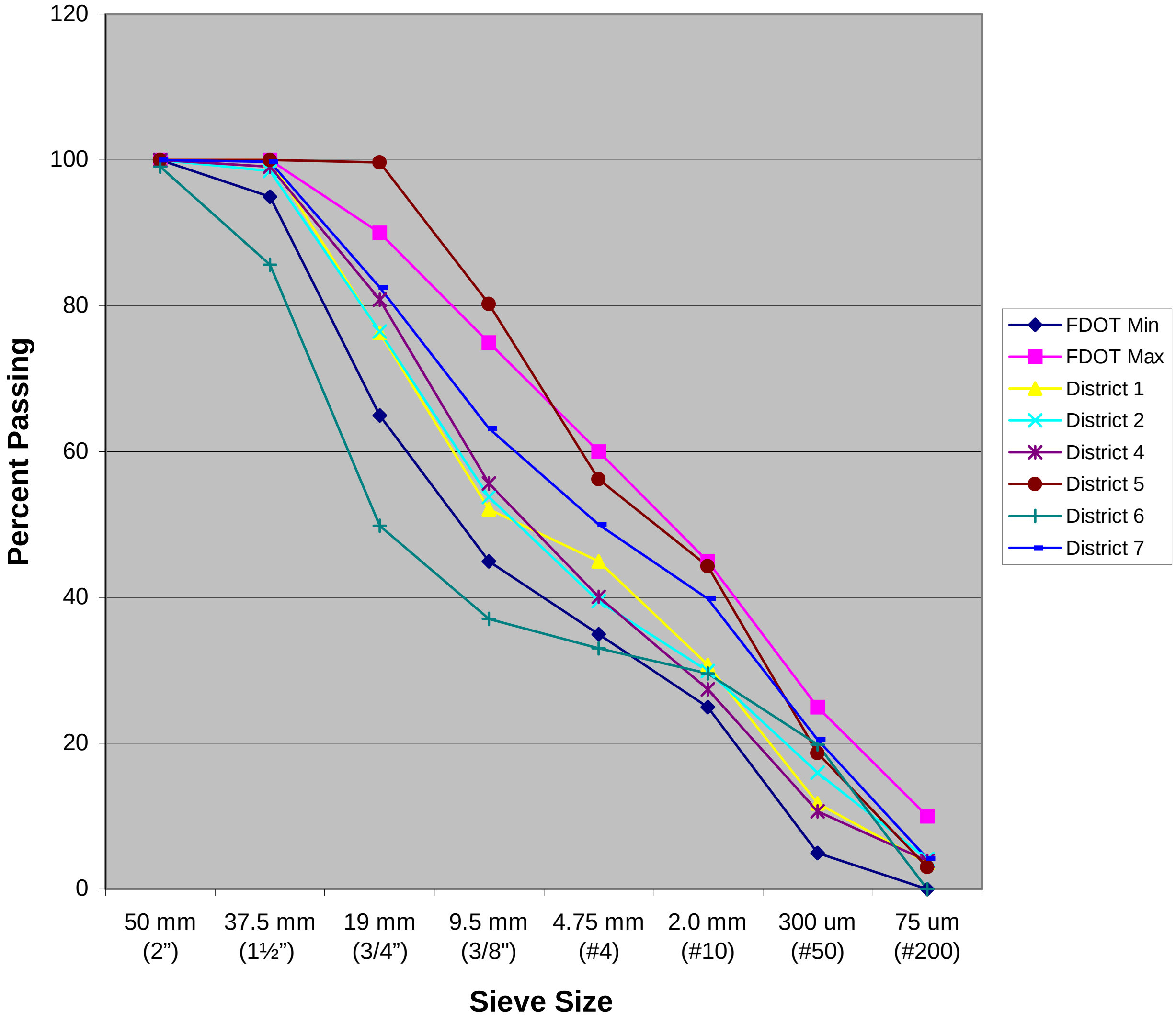


Figure 4.1 Average Particle Size Distribution

Table 4.8 RCA Average Gradation for The Total Samples

	Sieve No.	50 mm (2")	37.5 mm (11/2")	19 mm (3/4")	9.5 mm (3/8")	4.75 mm (# 4)	2 mm (# 10)	300 µm (# 50)	75 µm (# 200)
RCA Sample Number	1	100.0	100.0	84.6	62.6	47.6	35.9	13.3	2.8
	2	100.0	100.0	75.9	50.9	28.3	29.1	12.3	4.0
	3	100.0	100.0	70.5	45.2	34.2	26.1	11.1	3.4
	4	100.0	100.0	85.0	64.5	49.1	36.1	11.8	3.4
	5	100.0	100.0	68.0	42.8	31.2	23.8	10.6	3.7
	6	100.0	100.0	73.8	46.7	34.7	26.5	11.4	4.4
	7	100.0	99.2	72.7	51.5	36.8	27.0	12.6	4.7
	8	100.0	97.1	56.6	39.7	30.6	24.4	13.9	6.0
	9	100.0	98.9	82.5	53.4	38.1	28.9	15.8	3.3
	10	100.0	99.3	85.5	65.1	48.5	36.0	17.8	4.6
	11	100.0	97.4	81.0	58.5	44.5	34.7	20.9	2.6
	12	100.0	99.2	80.5	54.6	38.5	28.5	14.9	3.6
	13	100.0	100.0	99.8	72.8	55.6	44.6	16.8	3.4
	14	100.0	100.0	99.9	82.8	64.6	50.4	20.1	5.2
	15	100.0	100.0	99.9	81.6	58.3	45.6	19.9	3.0
	16	100.0	100.0	100.0	91.7	68.7	54.5	25.0	3.4
	17	100.0	100.0	99.2	74.5	41.4	31.6	13.5	3.3
	18	100.0	100.0	99.2	78.2	48.6	39.0	16.4	0.0
	19	100.0	100.0	88.4	70.7	56.7	45.5	21.6	4.4
	20	100.0	100.0	89.5	73.4	60.2	48.3	25.6	5.2
	21	100.0	100.0	75.5	56.5	44.0	34.7	16.0	3.6
	22	100.0	100.0	79.6	59.4	46.1	36.4	18.0	4.3
	23	100.0	98.7	81.8	62.2	50.1	40.6	22.0	4.4
	24	100.0	100.0	80.3	56.9	43.0	33.7	19.8	3.1
	25	100.0	97.7	73.1	51.2	37.4	26.0	11.9	3.5
	26	100.0	97.6	75.8	54.7	42.1	30.5	12.5	4.2
	27	100.0	100.0	85.8	68.6	51.2	30.3	10.8	3.2
	28	100.0	100.0	83.3	42.3	23.7	14.5	4.8	3.0
	29	100.0	100.0	86.3	61.5	46.0	35.5	13.5	5.4
Average		100.0	99.5	83.2	61.2	44.8	34.4	15.7	3.8
Standart Deviation		0.0	0.9	10.9	13.2	10.9	9.0	4.8	1.1
90% Confidence Interval	**Min.**	**100**	**98**	**65**	**40**	**27**	**20**	**8**	**2**
	Max.	**100**	**100**	**100**	**83**	**63**	**49**	**24**	**6**
FDOT Specifications Section 204	**Min.**	100	95	65	45	35	25	5	0
	Max.	100	100	90	75	60	45	25	10

4.2 Limerock Bearing Ratio

The limerock bearing ratio (LBR) test is the single most indicative test for the stability of a base course material, because it evaluates an aggregate's overall bearing and shear strength as compared to the standard strength of limerock, which is 800 psi (5.5 MPa). The FDOT LBR test (FM5 – 515) consists of using a 10-pound (0.0445 KN) piston hammer dropped from a height of 18 inches (45.7 cm) to compact a sample of base material. Load readings are recorded for each 0.01 in. (0.25 mm) of penetration. A curve showing the unit load versus penetration is then plotted. The unit load at 0.1 in. (2.54 mm) penetration is obtained from the plotted curve and presented as a percentage of the standard bearing strength of limerock. All LBR tests were conducted at the FDOT District 5 Office in Deland. The average LBR from all samples collected each month from all districts is given in Table 4.9. The asterisk shown in the table indicates the LBR test value that is below the FDOT standard LBR of 100.

Table 4.9 Average Limerock Bearing Ratios for All Districts

Sampling Month	FDOT Sect. 204	District 1	District 2	District 4	District 4(TSR)	District 5	District 6	District 7
December	>100	210	238	-	-	158	-	168
January	>100	209	189	-	-	175	-	122
February	>100	188	79*	-	-	124	-	151
March	>100	260	109	-	-	135	-	266
April	>100	197	150	-	-	238	-	131
May	>100	237	217	-	-	260	-	133
June	>100	251	238	208	-	-	-	-
July	>100	-	-	213	-	-	93*	-
August	>100	-	-	90*	143	-	67*	-
September	>100	-	-	208	317	-		-

*Does not meet FDOT Sect. 204 requirements.

Figure 4.2 shows a bar chart of average LBR from each district's samples compared against FDOT Section 204 Specifications (red line) for natural aggregates. Table 4.10 shows the arithmetic mean of LBR from each district, so that the outlier LBR values (in red) can be identified. Figure 4.3 shows the LBR values of arithmetic mean and arithmetic mean not counting outliers against the respective arithmetic mean (bar-chart) of each district. Figure 4.4 further shows the arithmetic mean LBR not counting the outliers from each district with respect to the LBR value (green color) from the RCA material used at UCF test sections. It is interesting to note that the LBR of 258 from RCA used at UCF test site is much higher than most of the samples. Excellent performance of RCA on UCF test sections is anticipated.

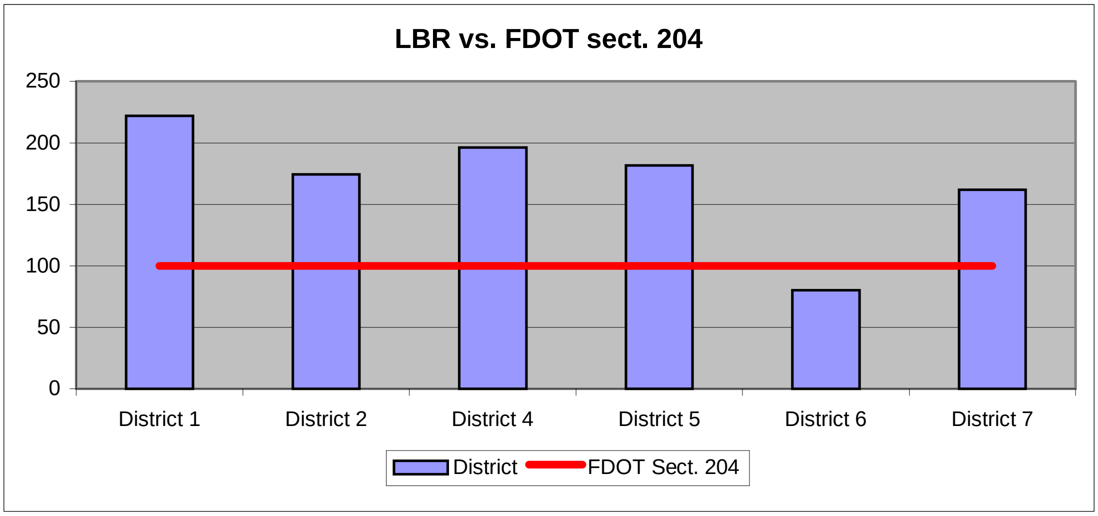


Figure 4.2 District average Limerock Bearing Ratios Compared against FDOT Specifications Section 204 for Natural Aggregates.

Table 4.10 Average LBR from Samples Collected at various District.

District Designation	Number of Samples	Limerock Bearing Ratio (LBR)							Arithmetic Mean
1	7	210.00	209.00	188.00	260.00	197.00	237.00	251.00	**221.71**
2	7	238.00	189.00	79.00	109.00	150.00	217.00	238.00	**174.29**
4	6	208.00	213.00	90.00	208.00	143.00	317.00		**196.50**
5	6	158.00	175.00	124.00	135.00	238.00	260.00		**181.67**
6	2	93.00	67.00						**80.00**
7	6	168.00	122.00	151.00	266.00	131.00	133.00		**161.83**
UCF-CATT	1	258.00							**258.00**
Total	**35**	**RCA Arithmetic Mean** →							**181.53**
		RCA Standard Deviation →							**61.31**
		RCA Arithmetic Mean not Counting Outlliners →							**197.60**

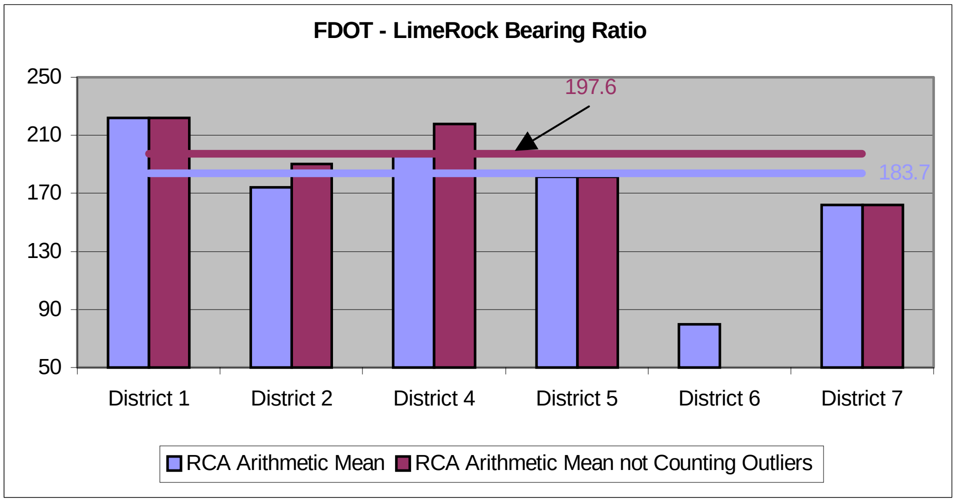


Figure 4.3 Average Limerock Bearing Ratios Presented by District.

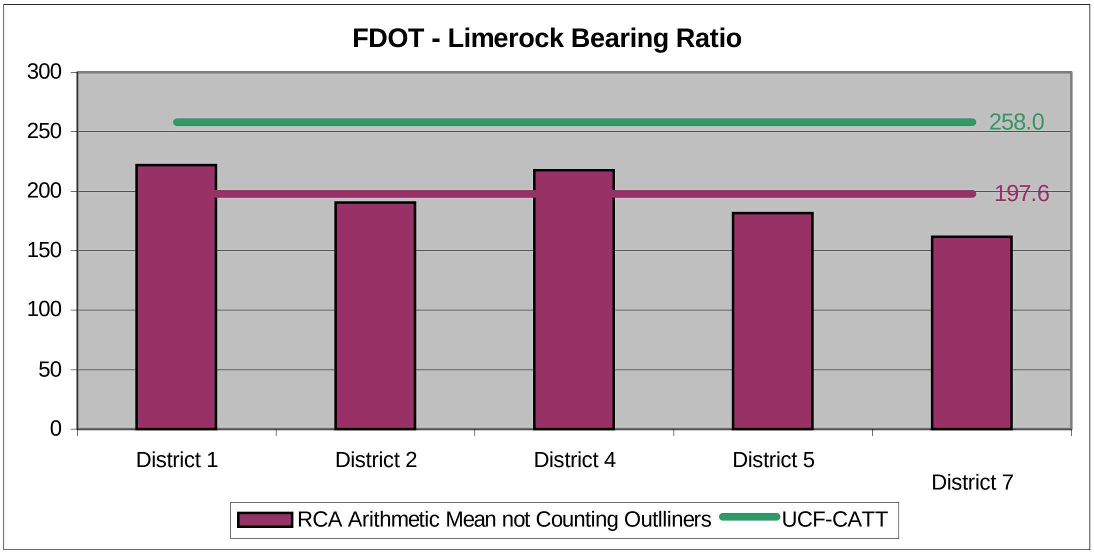


Figure 4.4 Average Limerock Bearing Ratio Compared to UCF-CATT Sample.

From the LBR test results shown in Table 4.10, it appears that the recycled concrete materials consistently provide very high LBR values with only a few outliers, particularly from District 6. The average LBR for District 6 was only 80 psi (552 kPa) because of the large amounts of foreign material presented in the samples. The overall LBR average of 181.71 surpasses the 100 requirement of FDOT Section 204 Specification. It concludes that the LBR for RCA may require a minimum of 120.

4.3 Los Angeles Abrasion Test

Los Angeles (LA) abrasion test (FM 1-T 096) has been extensively used as an indicator of the relative quality or competence of various sources of aggregates having similar mineral compositions. The test results do not allow appropriate comparisons between sources from different origin, composition, or structure. Specification limits founded on this test should be issued carefully by considering the available aggregate types and their performance history in specific uses.

4.3.1 Test Procedure

The Los Angeles abrasion test is a measure of degradation of mineral aggregate particles smaller than 1 ½ in. (37.5 mm) of standard grading resulting from a combination of actions including abrasion, impact, and grinding occurring in a rotating steel drum containing a number of steel spheres. While the drum rotates, the sample and the steel spheres are picked up by a shelf plate that carry them around until they are dropped to the opposite side of the drum creating an impact-crushing effect. Within the drum, the contents roll with an abrading and grinding action until the shelf plate impacts and the cycle is repeated. When the established number of revolutions is reached the contents are removed from the drum and the aggregate portion is sieved to measure the degradation as percent loss.

4.3.2 Test Results

The results of LA abrasion test from all samples are presented in Table 4.11. FDOT specification section 204 on LA abrasion loss is also listed in Table 4.11. FDOT LA abrasion loss of natural aggregates used for base courses is specified to be less than 45%. The average values of LA abrasion loss for the RCA samples are in the range of 41.62 to 47.60% as shown in Table 4.11. It is apparent that the most of these values fall within the FDOT acceptable parameter for natural graded aggregates. Figure 4.5 shows the bar chart of average RCA LA abrasion loss from each district against the standard 45% loss by FDOT Specification Section 204.

Table 4.12 shows the arithmetic means of LA abrasion for each district and total samples, and Figure 4.6 shows the bar-chart of each district's average as compared to the total average of 90% confidence interval, which is between 46.7 and 41.0 as shown in two red lines. LA abrasion loss of 39.4% shown by the green line is the test result of RCA used on UCF-CATT test sections. Since the LBR value of 275 from RCA tested at UCF site is also much greater than other samples, a lower value of LA abrasion loss in comparison to the others is expected.

Table 4.11 LA Abrasion Loss of All Samples.

Sampling Month	FDOT Sect. 204	District 1	District 2	District 4	District 4(TSR)	District 5	District 6	District 7
December	<45%	44.53%	42.75%	-	-	41.62%	42.23	44.46%
January	<45%	44.86%	45.14%*	-	-	42.67%	-	43.71%
February	<45%	47.60%*	44.40%	-	-	43.35%	-	44.59%
March	<45%	45.97%*	43.12%	-	-	42.79%	-	47.13%*
April	<45%	46.16%*	45.35%*	-	-	-	-	44.61%
May	<45%	45.77%*	43.71%	-	-	-	-	45.18%*
June	<45%	-	-	-	-	42.97%	-	-
July	<45%	-	-	42.39	-	43.58%	-	-
August	<45%	-	-	43.42	41.83	-	-	-
September	<45%	-	-	43.35	42.08	-	-	-

*Does not meet FDOT Sect. 204 requirements.

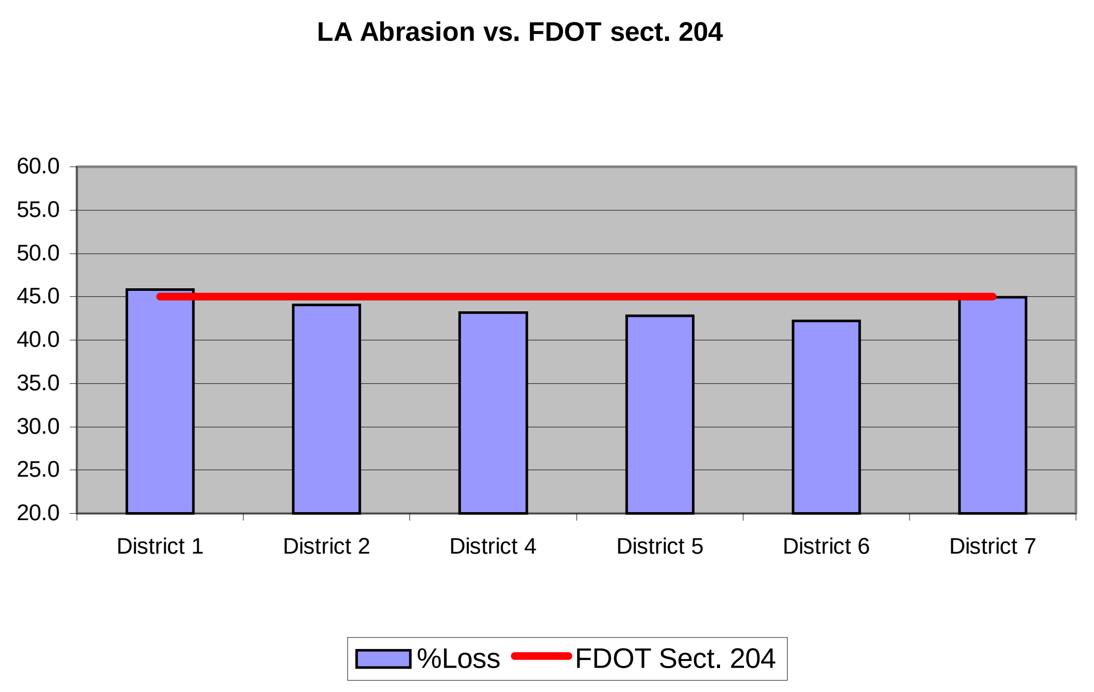


Figure 4.5 Average RCA LA Abrasion Loss Versus FDOT's Specifications Section 204 for Natural Aggregates.

Table 4.12 LA Abrasions Results

District	Number of	Los Angeles Abrasion Test						Arithmetic
Designatio	**Samples**	**Percent of Loss (%)**						**Mean**
1	6	44.53	44.86	47.60	45.97	46.16	45.77	**45.82**
2	6	42.75	45.14	44.40	43.12	45.35	43.71	**44.08**
4	5	42.39	43.42	42.50	41.83	42.08		**42.44**
5	6	41.62	42.67	43.35	42.79	42.97	43.58	**42.83**
6	1	42.23						**42.23**
7	6	44.46	43.71	44.59	47.13	44.61	45.18	**44.95**
UCF-CATT	1	39.44						**39.44**
Total	**31**	**RCA Arithmetic Mean**				→		**44.02**
		RCA Standard Deviation				→		**1.74**

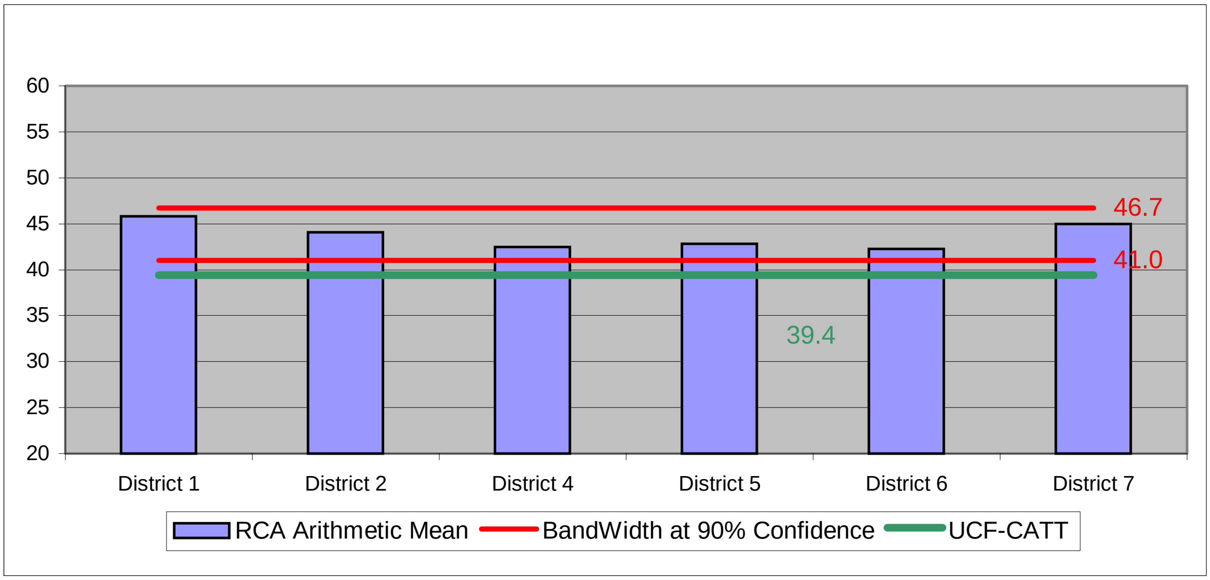


Figure 4.6 Comparison of Average LA Abrasion Loss from Each District, Total Average of 90% Confidence Interval, and UCF-CATT RCA Sample.

4.4 Soundness

Soundness is defined as the ability of the aggregate to withstand abrasion and/or crushing. It is very important to foresee the constructed pavement if the fines will be generated from the coarse aggregates under the actions of roller and traffic loads. Too much fines generated in the base course of a pavement system may affect the drainability of initial design. Soundness of aggregates can be tested by means of the sodium sulfate test, the Los Angeles abrasion test and a combination of compaction and sieve tests. RCA generally has a higher loss of soundness due to its mortar content. When the mortar is crushed, less grain interlock results, and more fines are created as stated in the literature review.

4.4.1 Sodium Sulfate Test

The sodium sulfate test (AASHTO-T104) is performed to determine an aggregate's resistance to disintegration by saturated solution of sodium sulfate. It is accomplished by repeated immersion of the aggregate in saturated solutions of sodium sulfate followed by oven drying to partially or completely dehydrate the salt that is precipitated in permeable pore spaces. The internal expansive force, derived from the re-hydration of the salt upon re-immersion, simulates the expansion of water on freezing. After completion of the immersion cycle, the aggregate sample is washed clean of all sodium sulfate, dried and weighed. The difference between the sample's original weight, and the weight after immersion in the sulfate solution is the loss in the test and is expressed as a percentage of the initial mass.

This test method furnishes information helpful in judging the soundness of aggregates subject to weathering action. Acceptable limits of 15% have been established by FDOT for graded aggregate bases. The RCA material sampled in December had a soundness loss much greater than 15% after 5 cycles of sodium sulfate test. Table 4.13 shows the test results from RCA samples collected in the month of December from Districts 1,2,5, and 7. District 2 shows the highest loss at 70%. The average soundness loss is about 52%, well above the FDOT specification of less than 15%.

Table 4.13 Percent Loss through Sodium Sulfate Test.

District	FDOT Sect. 204	December % Loss
1	<15%	57%
2	<15%	70%
5	<15%	39%
7	<15%	42%

From literature review, many countries and U.S. highway agencies have decided to waive the sodium sulfate test for recycled concrete aggregates. It is because the sodium sulfate will disintegrate the concrete aggregate during the test. Thus, the sodium sulfate test should be waived.

.

4.5 Sand Equivalent

The sand equivalent test is designed to measure the proportion of sand to clay within a sample. To achieve proper particle interlocking, it is necessary to have a minimum particle size distribution. The Florida Department of Transportation requires that aggregates passing through 4.75 mm sieve shall have a sand equivalent value of not less than 28%. The RCA samples tested in this project were found to have sand equivalent values much higher than 28%, as shown in Table 4.14. Thus, as far as sand equivalent is concerned, the sampled RCA materials are meeting the requirement of FDOT Section 204.

Table 4.14 Sand Equivalent Results.

Districts	FDOT # 204	Sampling Date (%)		
		December	January	August
1	>28%	75	78	-
2	>28%	81	69	-
4	>28%	-	-	61
4 (TSR)	>28%	-	-	57
5	>28%	79	70	-
6	>28%	-	-	47
7	>28%	84	75	-

4.6 Heavy Metals

Florida plays a leading role in environmental control by closely monitoring pollution. As part of this effort, it is important to analyze heavy metal content within recycled concrete aggregates. The heavy metal bracket includes cadmium, chromium, aluminum, nickel, iron, zinc, copper, and lead. Lead is the most important of these metals. The Environmental Protection Agency (EPA) has set the limit on lead emissions to 5 parts per million (ppm). Even extremely low levels of lead can cause health problems such as lead poisoning. One of the most prevalent sources of lead in waste materials is paint. Legislation halting the production of paint over 0.06% in lead content has successfully reduced the amount of lead released into the environment; however, large amounts of lead-based paint persist in and around many homes. It is estimated that three million tons of lead remain in fifty seven million American homes (EPA 1996). Tables 4.15 through 4.20 list the content of heavy metals tested in the samples collected at each district.

Table 4.15 Content of Heavy Metals in District 1 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
December	ND	ND	ND	5200	ND	6200	140	ND
January	ND	ND	ND	3500	ND	18000	39.1	ND
February	ND	ND	ND	5100	ND	5400	25.6	ND
March	ND	ND	ND	3700	ND	4100	16.4	ND
April	ND	ND	ND	4800	ND	6000	29	ND
May	ND	ND	ND	4200	ND	4400	ND	ND

Table 4.16 Content of Heavy Metals in District 2 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
December	ND	ND	ND	4408	ND	4200	99	ND
January	ND	ND	ND	4000	ND	13000	ND	ND
February	ND	ND	ND	2800	ND	3100	ND	ND
March	ND	ND	ND	4800	ND	4000	ND	ND
April	ND	ND	ND	4400	ND	4833	ND	ND
May	2	ND	13	3973	3	3980	47	22

Table 4.17 Content of Heavy Metals in District 4 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
July	12*	ND	16	2252	4	2525	84	15
August	ND	ND	ND	4600	ND	4600	78.2	ND
September	ND	ND	ND	4500	ND	4600	380	ND

*Lead content over 5ppm.

Table 4.18 Content of Heavy Metals in District 5 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
December	ND	ND	ND	5400	ND	7300	120	ND
January	ND	ND	ND	3600	ND	4600	24.8	ND
February	ND	ND	ND	4600	ND	5200	33	ND
March	ND	ND	ND	4600	ND	5300	26	ND
June								
July								

Table 4.19 Content of Heavy Metals in District 6 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
July	ND	ND	16	5501	12	4103	80	16
August								
September								

Table 4.20 Content of Heavy Metals in District 7 (Parts per million)

Month	Lead	Cadmium	Chromium	Aluminum	Nickel	Iron	Zinc	Copper
December	ND	ND	ND	4400	ND	5400	110	ND
January	ND	ND	ND	4600	ND	4600	78.2	ND
February	ND	ND	ND	4500	ND	4600	380	ND
March	ND	ND	ND	5200	ND	4600	32	ND
April	ND	ND	ND	4500	ND	5300	53	ND
May	ND	ND	ND	4100	ND	3700	ND	ND

*Lead content over 5ppm.

As seen from Tables 4.16 and 4.17, the presence of lead in some RCA samples at Districts 2 and 4 is possibly related to the presence of lead-paint in the demolished concrete. The highest observed lead content of 12ppm from one sample at District 4 is clearly over the 5-ppm EPA limit. Since this is only one random sample, it may not represent the material characteristics of a full profile.

4.7 Asbestos

Since demolitions comprise approximately 10% of all reported asbestos related activities according to EPA (EPA 1989), state officials require that all buildings or structures prior demolition must first be inspected and authorized clear of asbestos. Thus, the recycled concrete aggregates coming from demolished structures must be asbestos free.

Samples were collected from four districts and submitted for asbestos testing. These were:

- District 1 samples collected in January, February, March
- District 2 samples collected in January, March
- District 5 samples collected in January, February, March
- District 7 samples collected in January, March

An independent laboratory, Universal Engineering Sciences in Orlando, conducted the testing. They drew the following conclusion: “The laboratory analytical results indicated that asbestos fibers were not detected in any of the samples of crushed concrete analyzed.” Given the results of this study and the requirement of pre-demolition inspection, the test for asbestos in RCA may be eliminated.

4.8 Modified Proctor Compaction Test

The modified Proctor compaction test (FM 5 -521) was used to determine the optimum moisture and the maximum dry density of coarse aggregate. Photograph 4.1 shows the compaction apparatus performing the modified Proctor compaction test at the UCF laboratory.

Photograph 4.1. UCF Proctor Compaction Test

4.8.1 Test Procedure at UCF

In order to adequately prepare a test specimen, sufficient quantities of the prospective material were selected from a RCA sample. In this study, there were approximately 48 pounds (22kg) of RCA collected each month at each district in labeled bags.

Laboratory preparation of a specimen involved extraction of a small portion of RCA material from the sample bags and through air-drying in a pan. Before the samples were screened through a 19 mm (¾ in.) sieve, some aggregations were broken apart without crushing individual particles. All particles retained on the 19 mm (¾ in.) sieve were discarded. Four specimens were made from each RCA sample and the dry unit weight of each specimen was determined.

Before the compaction test, the test specimen was added with different amount of pre-weighted water, thus, the moisture content in each specimen was predetermined. This moisture content was then checked with the moisture content calculated from the actual weights of wet and dry specimen upon the completion of the compaction test. The results of compacted dry unit weight, γ_d, versus its respective moisture content, ω, for all RCA samples were plotted in the compaction curves shown in Appendix A.

4.8.2 Test Results

The compaction tests were conducted simultaneously at UCF and the FDOT District 5 laboratories. Tables 4.21 and 4.22, and Figures 4.7 and 4.8 present the UCF results, while, Tables 4.23 and 4.24, and Figures 4.9 and 4.10

are the results of District 5. An arithmetic mean and a standard deviation were also computed as shown in each table. Figures 4.11 and 4.12 are the bar-charts showing the comparison of the resulting average dry unit weights and optimum moisture contents performed by UCF and FDOT laboratories. Although, there are some variations in the results of the maximum dry unit weight and the optimum moisture content from the two agencies, the arithmetic means of the dry unit weight (113.8 lb/ft^3 (17.9 kN/m^3) of UCF vs. 114.8 lb/ft^3 (18.1 kN/m^3) of FDOT), and the moisture content (11.2% of UCF vs. 12.1% of FDOT) are very close. A standard of minimum dry unit weight of 110 lb/ft^3 (17.3 kN/m^3) and optimum moisture content of 11% may be expected for the qualifications of RCA.

Table 4.21 RCA Dry Unit Weight Tested at UCF Lab.

District Designation	Number of Samples	Dry Unit Weight (lb/ft^3)						Arithmetic Mean
1	6	109.6	109.8	111.7	107.7	111.7	115.0	**110.9**
2	6	114.2	117.2	117.6	115.2	116.6	115.8	**116.1**
4	5	114.8	113.0	113.7	104.9	113.7		**112.0**
5	6	113.5	108.5	113.6	113.2	121.3	121.5	**115.3**
6	1	111.0						**111.0**
7	6	112.7	112.7	117.1	114.7	115.0	116.0	**114.7**
Total	**30**	**RCA Arithmetic Mean** →						**113.8**
		RCA Standard Deviation →						**3.6**

Note: 1 lb/ft^3 =0.157 kN/m^3

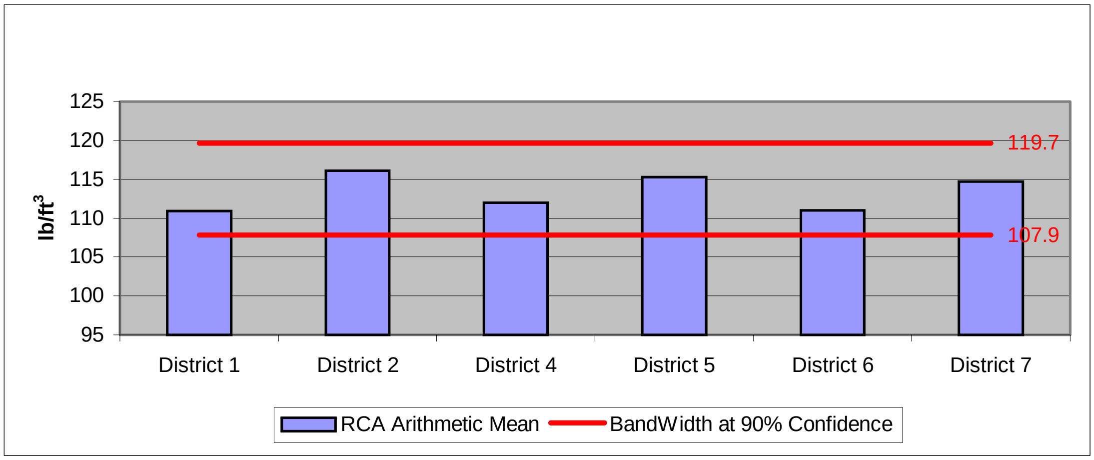


Figure 4.7 Dry Unit Weight Average by District and a 90% Confidence Interval (UCF Lab.).

Table 4.22 RCA Optimum Moisture Content Tested at UCF Lab.

District Designation	Number of Samples	Optimum Moisture Content (OMC) (%)						Arithmetic Mean
1	6	10.2	11.4	10.6	10.6	10.9	10.9	**10.8**
2	6	10.7	10.4	10.7	10.1	10.5	10.8	**10.5**
4	5	11.8	12.5	11.9	10.7	12.0		**11.8**
5	6	11.1	11.9	10.3	10.1	11.6	11.8	**11.1**
6	1	12.8						**12.8**
7	6	10.7	10.7	11.5	12.5	12.0	11.8	**11.5**
Total	**30**	**RCA Arithmetic Mean** →						**11.2**
		RCA Standard Deviation →						**0.8**

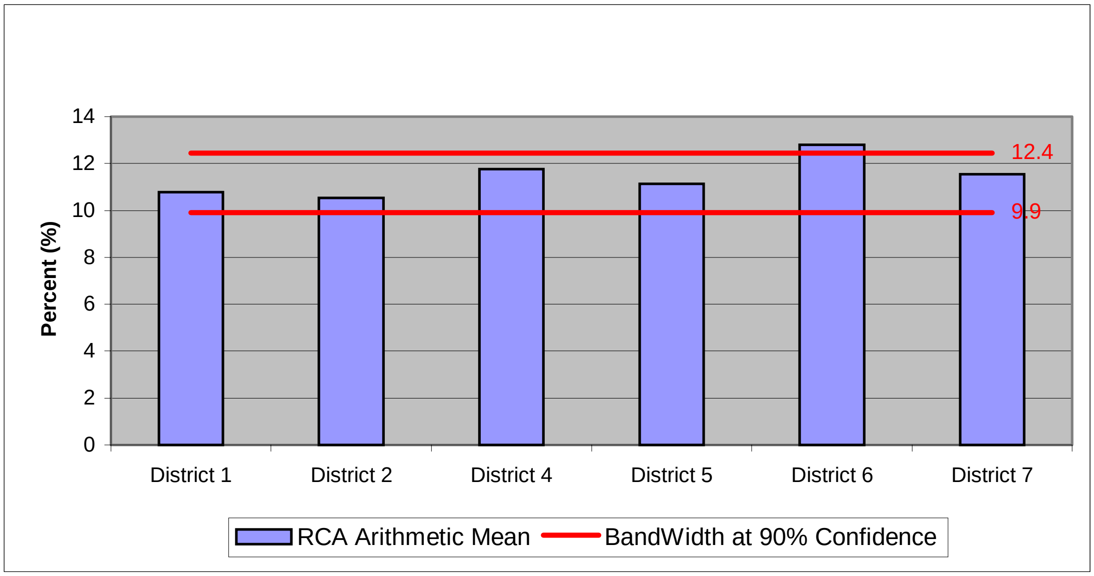


Figure 4.8 Optimum Moisture Content by District and a 90% Confidence Interval (UCF Lab.).

Table 4.23 RCA Dry Unit Weight Tested at FDOT Material Office Lab.

District Designation	Number of Samples	Dry Unit Weight (lb/ft^3)						Arithmetic Mean
1	6	114.90	114.80	115.30	112.70	116.80	115.00	**114.92**
2	6	115.70	111.50	112.50	116.80	118.80	117.60	**115.48**
4	6	111.80	111.00	109.50	109.10	110.10	115.10	**111.10**
5	5	114.30	115.00	117.50	120.30	120.30		**117.48**
6	2	109.80	103.20					**106.50**
7	5	118.80	118.80	119.50	117.10	116.20		**118.08**
UCF-CATT	1	119.00						**119.00**
Total	**31**	**RCA Arithmetic Mean** →						**114.80**
		RCA Standard Deviation →						**3.94**
		RCA Arithmetic Mean not Counting Outliers →						**115.19**

Note: 1 lb/ft^3 =0.157 kN/m^3

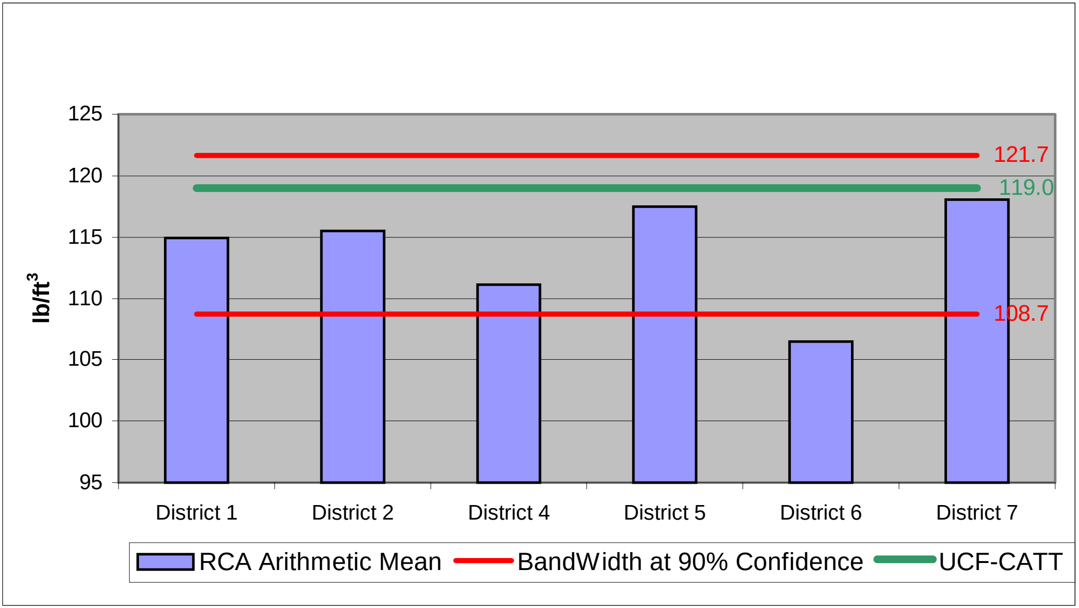


Figure 4.9 Dry Unit Weight Average by District and a 90% Confidence Interval (FDOT Lab.).

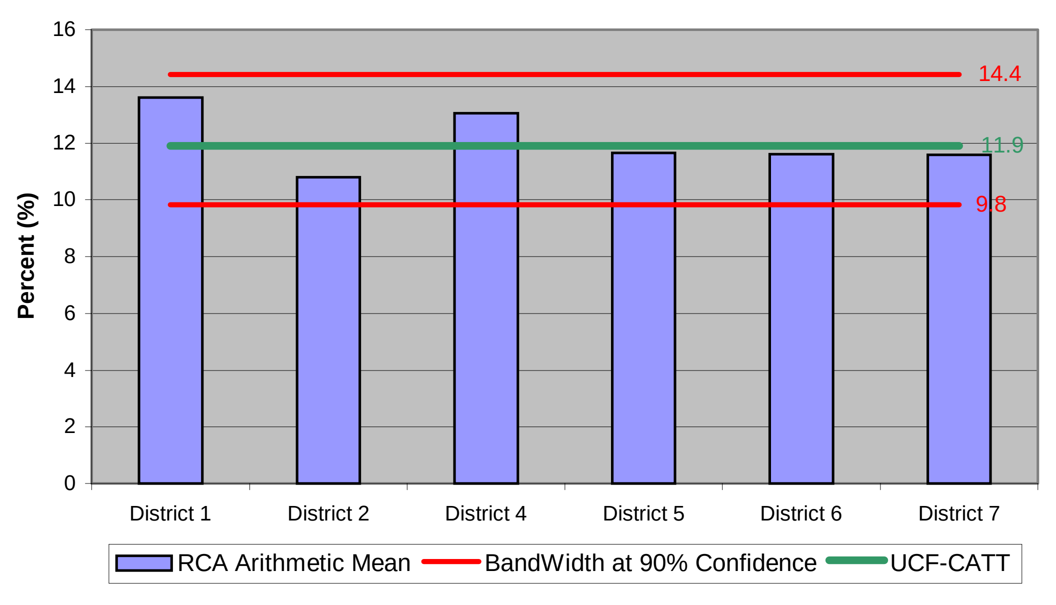


Figure 4.10 RCA Average Optimum Moisture Content by District, 90% Confidence Interval, and UCF-CATT Sample.

Table 4.24 RCA Optimum Moisture Content Tested at FDOT's Material Office Lab.

District Designation	Number of Samples	Optimum Moisture Content (OMC) (%)						Arithmetic Mean
1	6	14.40	13.80	13.10	13.60	12.90	13.90	**13.62**
2	6	12.70	7.60	9.50	12.20	11.40	11.30	**10.78**
4	6	13.70	13.00	13.60	12.30	11.80	13.90	**13.05**
5	5	12.20	11.70	11.90	11.70	10.70		**11.64**
6	2	11.60	11.60					**11.60**
7	5	11.60	10.90	12.30	11.20	11.90		**11.58**
UCF-CATT	1	11.90						**11.90**
Total	**31**	**RCA Arithmetic Mean**				→		**12.13**
		RCA Standard Deviation				→		**1.39**

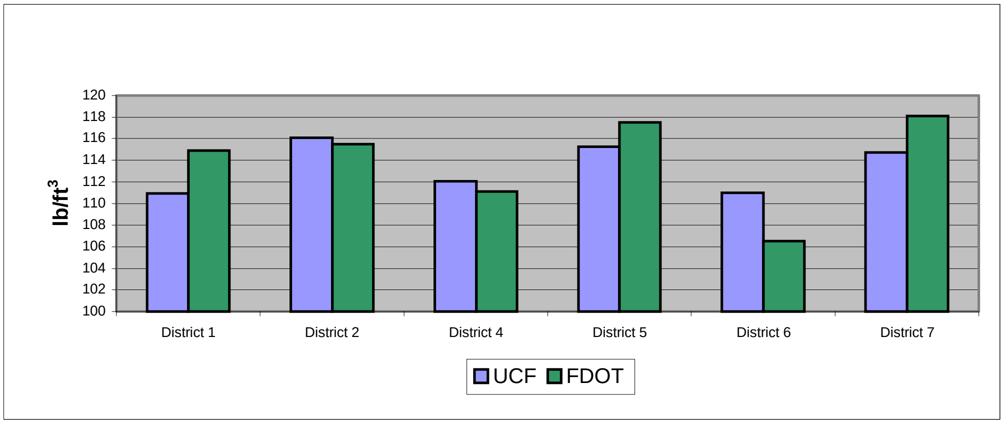


Figure 4.11 RCA Dry Unit Weight Comparison.

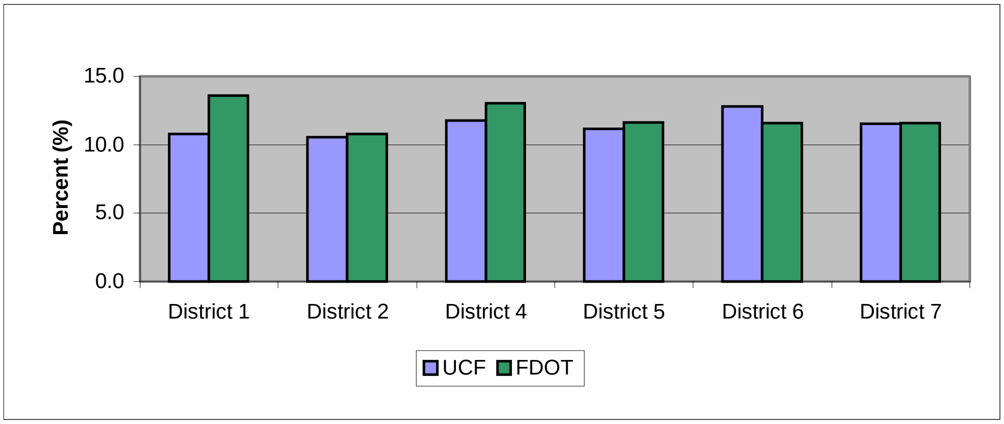


Figure 4.12 RCA Optimum Moisture Content Comparison

4.9 Hydraulic Conductivity (Permeability) Test

There is a tradeoff in base course properties between the ideal gradation for maximum stability and the ideal gradation for permeability (the flow of water through soils). The inclusion of fines in a gradation provides added support to the large soil particles in a base course, therefore, providing superior load supporting strength. Gradation with only a small percentage of fines, on the other hand, permits water to readily flow out of base courses, and therefore, minimizes the risk of premature pavement failures. Ideally, for good pavement performance, the permeability of granular base (aggregates) should be 0.283 ft/day (10^{-4} cm/s) or greater (Senior, 1992).

4.9.1 Test Procedure

Several instruments in the geotechnical laboratory such as the permeameter, pressure chamber, and consolidometer can be used to determine the value of hydraulic conductivity, K. A common feature of all these test methods consist of a soil sample placed in a small cylindrical receptacle representing a one-dimensional soil configuration through which the circulating liquid is forced to flow. Important considerations regarding laboratory tests for measuring K values are related to the soil sampling procedure, preparation of the test specimen, and circulating liquid (in this case water). The sampling process, if not properly conducted, usually disturbs the matrix structure of the soil and results in a misrepresentation of the actual field conditions. Undisturbed sampling of soils is possible, but it requires the use of specially designed techniques and instruments (Klute and Dirksen 1986). Photograph 4.2 shows the laboratory testing of RCA hydraulic conductivity.

Photograph 4.2 Hydraulic Conductivity Test.

Depending on the flow pattern imposed through the soil sample, standard laboratory tests for measuring hydraulic conductivity are a constant-head test with a steady-state flow regimen and a falling-head test with an unsteady-state flow regimen.

The constant-head test is employed in this project using Equation 4.1.

$$K = \frac{Q \times L}{A \times \Delta h \times t} \tag{4.1}$$

Where:

$Q =$ Volume of water collected
$L =$ Length of soil specimen
$A =$ Area of cross section of the soil specimen
$t =$ Duration of water collection
$\Delta h =$ Head difference from initial head and final head at the time t

To accurately determine the K value, it is recommended to evaluate several test samples under the various head differentials, Δh. It is also recommended to collect sufficient water in the measured volume.

4.9.2 Test Results

The result of K values is tabulated in Table 4.25 from all samples collected in this project. Table 4.26 presents the K values with arithmetic mean and standard deviation. Since the K values of 2.00 ft/day (0.61 m/day) and 2.20 ft/day (0.67 m/day) from District 5, 0.09 ft/day (0.027 m/day) from District 6, and 0.05 ft/day (0.15 m/day) from District 7 were either too large or too small. These values were considered outliers.

The average K value with and without counting outliers from each district is plotted in bar chart as shown in Figure 4.13. The average K value of 0.67ft/day (0.21 m/day) (not counting outliers) is plotted in Figure 4.14 along with K value of 0.72 ft/day (0.22 m/day) from UCF RCA material using for test sections. From the test results, it appears that most of the RCA material will meet the permeability requirement.

Table 4.25 Permeability Test Results of K Values (ft/day)

Month	District 1	District 2	District 4	District 4 (TSR)	District 5	District 6	District 7
December	0.50	0.60	-	-	2.00	-	0.38
January	0.80	0.20	-	-	2.20	-	0.28
February	0.60	0.30	-	-	1.00	-	0.05
March	1.25	0.70	-	-	0.95	-	0.20
April	0.80	0.60	-	-	0.80	-	0.25
May	1.40	0.70	-	-	0.60	-	0.20
June	-	-	-	-	-	-	-
July	-	-	0.70	-	-	0.09	-
August	-	-	1.20	1.30	-	-	-
September	-	-	0.90	0.19	-	-	-

1 ft. = 0.3048 m.

Table 4.26 RCA Permeability Tested at UCF lab.

District Designatio	Number of Samples	Permeability (K) (ft/day)						Arithmetic Mean
1	6	0.50	0.80	0.60	1.25	0.80	1.40	**0.89**
2	6	0.60	0.20	0.30	0.70	0.60	0.70	**0.52**
4	5	0.70	1.20	0.90	1.30	0.19		**0.86**
5	6	2.00	2.20	1.00	0.95	0.80	0.60	**1.26**
6	1	0.09						**0.09**
7	6	0.38	0.28	0.05	0.20	0.25	0.20	**0.23**
UCF-CATT	1	0.70						**0.70**
Total	**31**	**RCA Arithmetic Mean** →						**0.72**
		RCA Standard Deviation →						**0.52**
		RCA Arithmetic Mean not Counting Outliers →						**0.67**

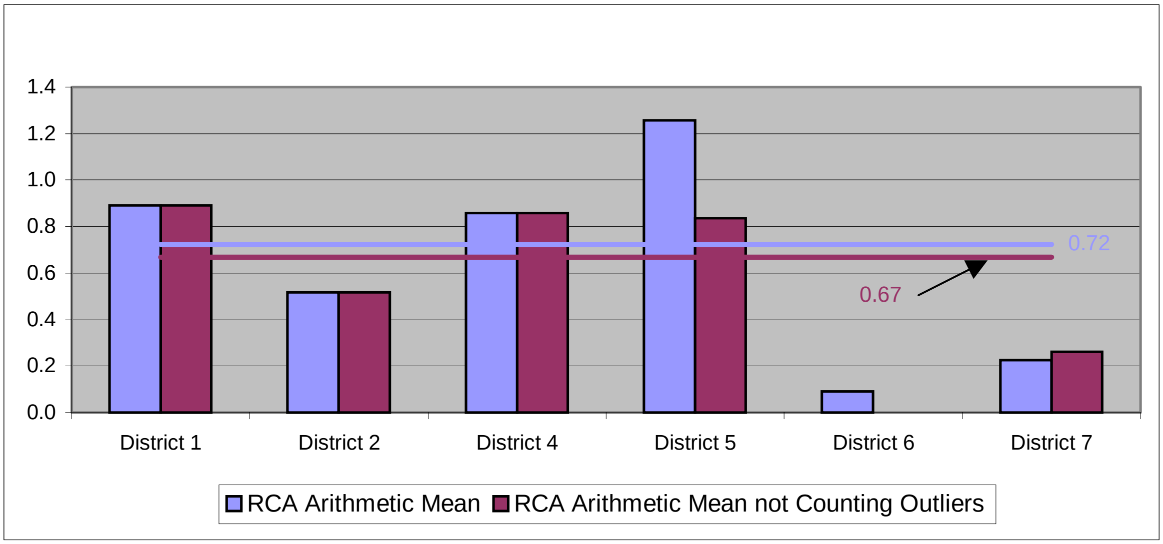


Figure. 4.13. Comparison of RCA Arirhmetic Mean K Vaues with and without outliers

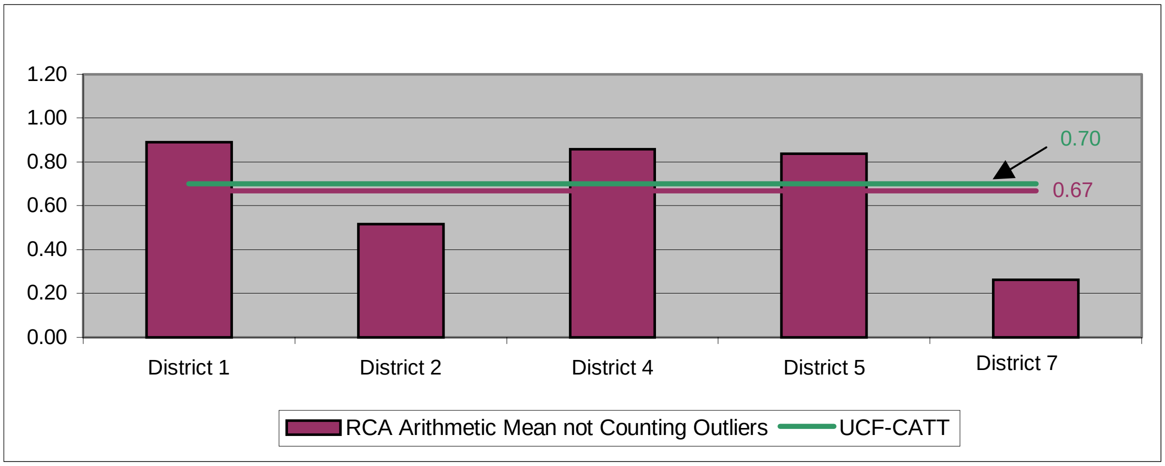


Figure 4.14 Comparison of RCA Arirhmetic Mean K Values without Outliers to UCF Permeabilty

4.10 Impurities

Impurities (foreign material) present in RCA are one of the biggest concerns surrounding the use of this material in construction. Besides a displeasing look, excessive amounts of foreign materials also affect the material's workability. Handling of glass, nails, rebar, and wood shards in RCA is considered a safety hazard. In addition, excessive foreign material will affect RCA's shear and compressive strengths and its performance as a construction material.

To determine the amount of impurities, samples were passed through sieves to separate the aggregate into its different sizes, thus facilitating the removal of foreign materials by means of visual inspection. Impurities were classified into different categories such as wood chips and paper, plastics, steel, asphalt, brick, and tile. The resulting percentage of impurities by weight from all samples is presented in Table 4.27. Further, Figure 4.15 shows the percent by weight of foreign materials from the District 1 samples, and Figure 4.16 shows the percent by weight of foreign materials from December samples in Distracts 1,2,5 and 7.

The average impurity content shown in the table does not specify the types and the volume of the foreign materials. Wood, for example, has an average density of about 47 lb/ft^3 (750 kg/m^3). This means that the wood from District 6 for the month of July sample would represent about 0.09 ft^3 ($0.0025m^3$).

Table 4.27 Percentage of Impurities by Weight

Month	District 1	District 2	District 4	District 4(TSR)	District 5	District 6	District 7	RCA Average
December	4.01%	2.30%	-	-	2.05%	-	2.76%	
January	2.11%	2.49%	-	-	0.93%	-	2.26%	
February	2.50%	3.49%	-	-	2.17%	-	2.24%	
March	1.43%	2.02%	-	-	0.72%	-	2.22%	
April	3.04%	1.20%	-	-	-	-	2.34%	
May	2.26%	3.45%	-	-	-	-	1.69%	
June	-	-	-	-	0.30%	-	-	
July	-	-	2.53%	-	0.32%	15.30%	-	
August	-	-	2.43%	0.86%	-	14.97%	-	
September	-	-	2.45%	1.27%	-	11.11%	-	
Average	2.56%	2.49%	2.47%	1.07%	1.08%	13.79%	2.25%	**3.67%**
Average without District 6								**1.99%**

Generally, asphalt was the most predominant type of impurity (see Figures 4.15 and 4.16). The total amount of impurities from each site ranged from a minimum of 0.30% to a maximum of 15.30% by weight as shown in Table 4.27. The impurity average was found to be 3.67% with District 6 included, and 1.99% without District 6 samples. Both average percentages are considered to be a negligible amount. The quantity of impurities found in District 6 samples is conceder to be an excess of what should be allowed in acceptable material for road base. These numbers can probably be lowered without incurring significant costs by employing further screening of the material. One such method is the use of industrial fans to separate lightweight materials such as wood and plastics as they descend from one beltway to another and the use of a large magnet to separate any metals.

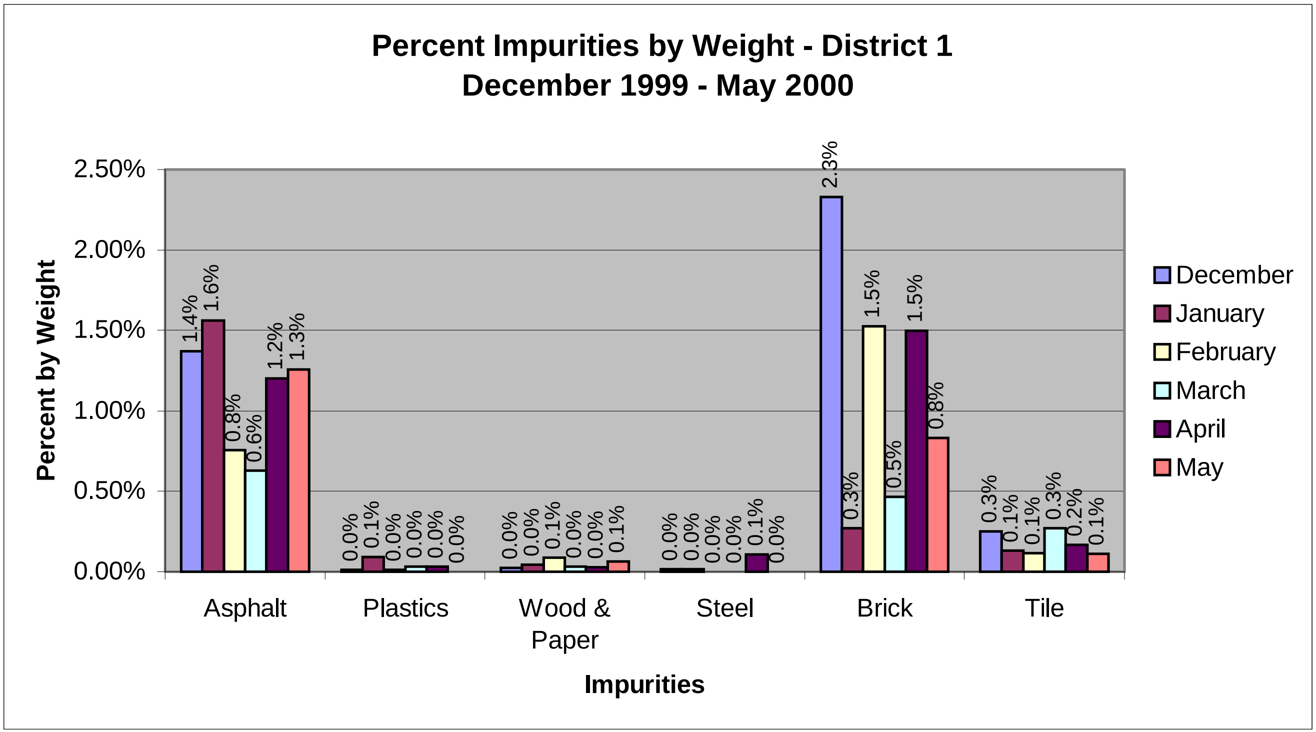


Figure 4.15 Percent Impurities by Weight - District 1 (December 1999 - May 2000).

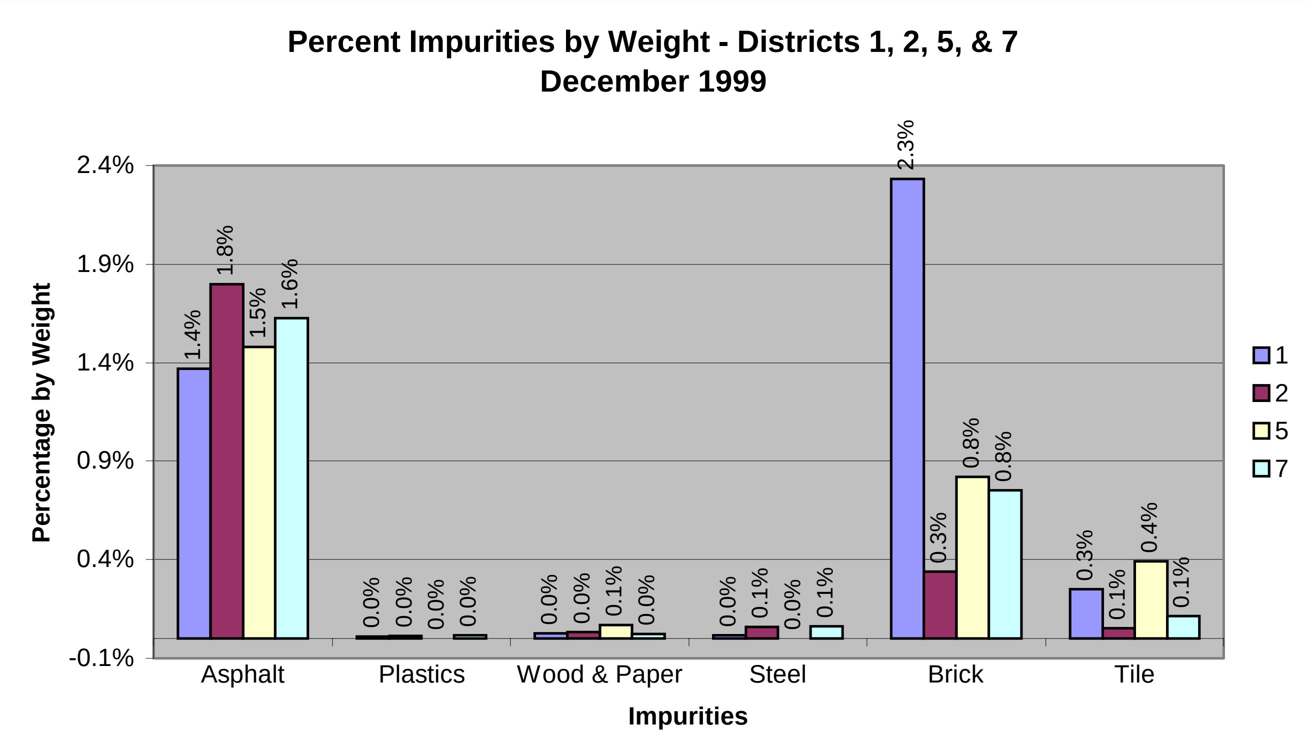


Figure 4.16 Percent Impurities by Weight - Districts 1, 2, 5, & 7 December

CHAPTER 5

PERFORMANCE OF THE TEST SECTIONS

One of the objectives of this study is to conduct the performance test of the recycled concrete aggregate (RCA) as a substitute for the natural coarse aggregates, such as Limerock, used as a base material for Asphalt Concrete (AC) pavement. The following chapter will describe the process of preparing the test sections at the University of Central Florida Circular Accelerated Test Track (UCF-CATT) and to discuss the test results.

5.1 UCF - CATT

The UCF-CATT was built by the Florida Department of Transportation in 1989 for the purpose of testing bridge expansion joints. The testing machine consists of three dual wheel assemblies on three half axles that cover a diameter of 50 ft (15.2m) to the centerline of a 6 ft (1.8 m) wide pavement. The track is divided into two halves, which are separated by two bridge sections that span a length of 12 ft (3.7 m).

The test track has three sets of dual truck tires that travel on the pavement in a circular path guided by radial arms. The loading on dual-wheel assemblies is capable of carrying up to 30,000 lbs (133.5kN) per wheel. The details of the UCF-CATT facility can be found in “Design of a Full-Scale Apparatus for Testing of Bridge Expansion Joints” (Bergeson, 1990).

5.2 RCA as a Base Course

A base course is defined as the layer of material that lies immediately below the wearing surface of a pavement. In the case of asphalt pavements, the base course lies underneath the surface course. Hence, the base course must possess high resistance to deformation in order to withstand the high tire pressures imposed on the pavement. The function of base courses under a flexible pavement is primarily to increase the load supporting capacity of the pavement system by distributing the load through a finite thickness of pavement components (Witzack, 1976). Consequently, in a satisfactory design, the thickness of the base course should be sufficient to prevent the overstressing of the subgrade, to provide good drainage, and to protect against frost action. In order to successfully use recycled concrete aggregate base course, it is important to understand the functions of the base course and the factors which may affect the performance. The experimental test sections at the test track may provide some needed information.

5.3 AASHTO Design of Flexible Pavement Sections

Using the FDOT Design Manual Table 5.2 for a Rural Arterial road to be rehabilitated, the reliability (R), which is the probability of achieving the design life, required by FDOT is R = 94%. Also from Design Manual Table A.6B with given R, M_R, ESAL, the required structural number (SN_R), which is an index number representing the required strength of the pavement structure, is SN_R = 2.7. Therefore, the SN_R for the test sections must be greater than 2.7. The following table shows the calculation of the SN_R for each test section. Notice that the layer coefficients given in Table 5.1 are based on literature values, not from the results of this study. Since the structural numbers calculated in Table 5.1 are well above 2.7 of FDOT specification, the thickness components may be considered adequate for use at UCF-CATT test sections.

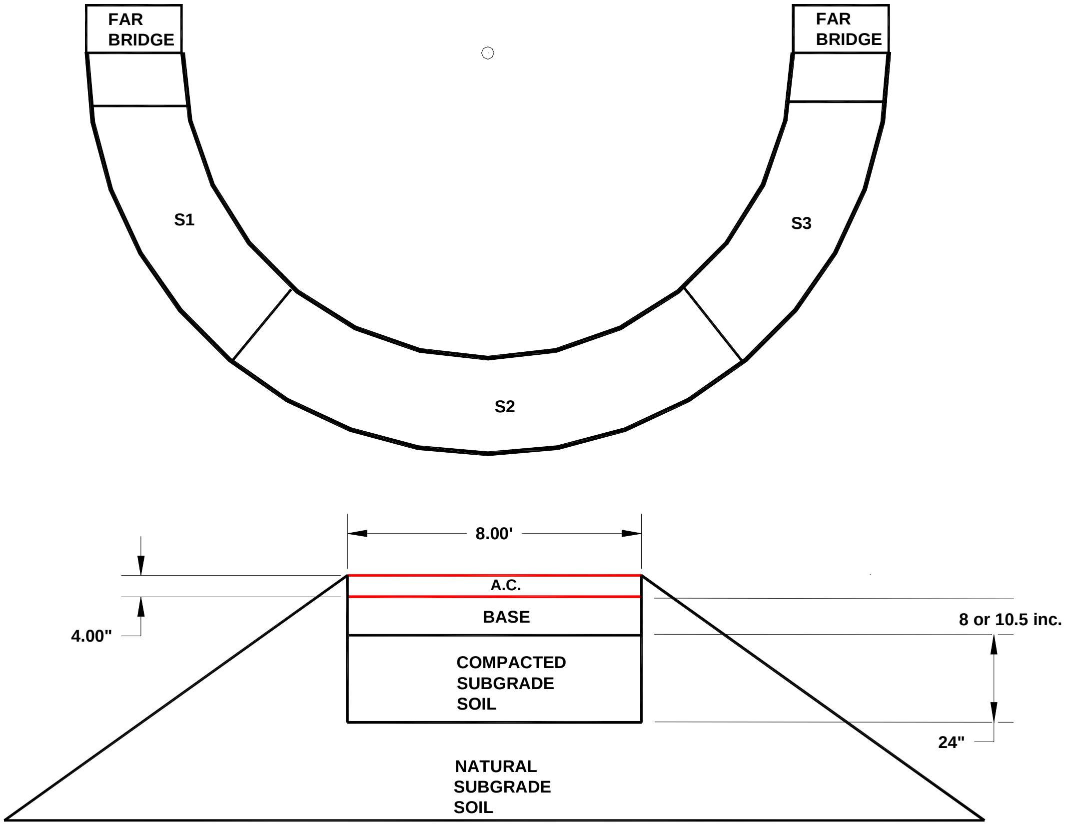
Table 5.1 Structural Number Calculations for Flexible Pavement Cross-Sections.

GROUP	LAYER TYPE	LAYER COEFF. Per mm
Structural Courses	Type S-I	0.017
Base Courses	Limerock (LBR 100)	0.007
Base Courses	RCA (LBR 100)	0.006
Stabilized Sub-Grade	Type B	0.003

LAYER	Section 1	Section 2	Section 3
Friction course	None	None	None
Structural Course	**1.73**	**1.73**	**1.73**
Thickness	4 in (101.6 mm)	4 in (101.6 mm)	4 in (101.6 mm)
Type	S-1	S-1	S-1
Base Course	**1.22**	**1.60**	**1.87**
Thickness	8 in (203.2 mm)	10.5 in (266.7 mm)	10.5 in (266.7 mm)
Type	RCA	RCA	Limerock
TOTAL SN_R	**2.95**	**3.33**	**3.59**

5.4 Test Sections Layout

Figure 5.1 shows the layout of the test sections and the respective cross section. Three test sections on half of the track were deployed for the performance test of base courses in the flexible pavement system.



Section	Base Course	Thickness (inch)
1	RCA	8.0
2	RCA	10.5
3	Limerock	10.5
All Sections	Compacted Subgrade Soil	24

Figure 5.1. Test Section Layout and Cross Section

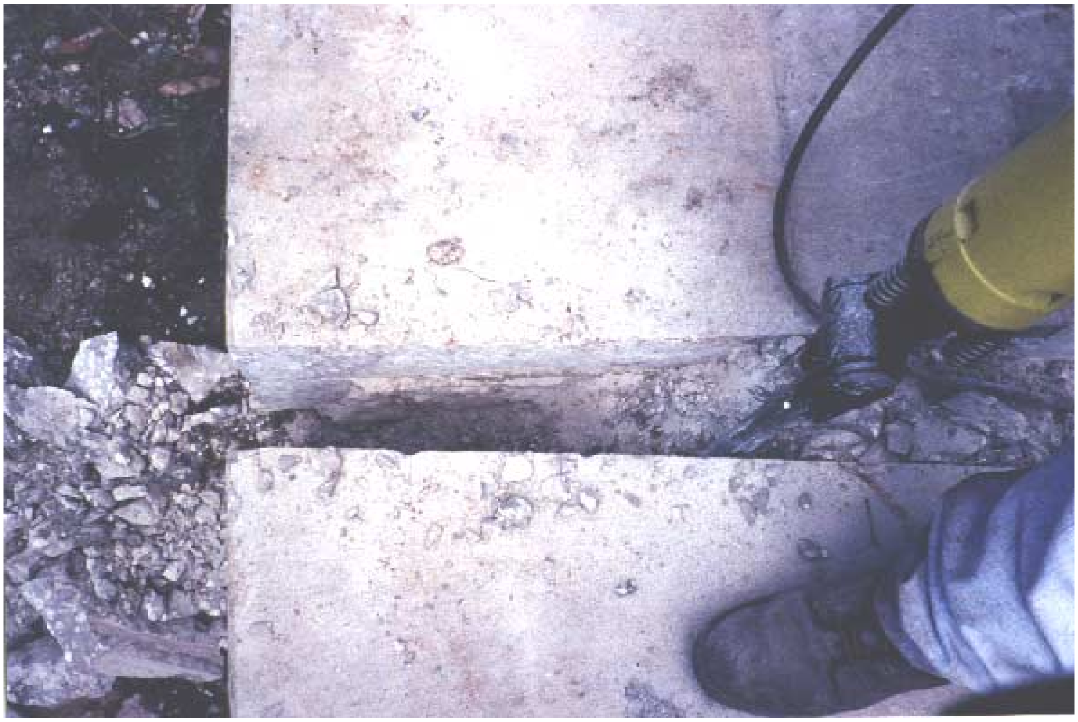
As shown in Figure 5.1, section 1 was constructed with an 8 in. (20.3 cm) thick RCA base, section 2 with a 10½ in. (26.7 cm) thick RCA base, and section 3 with a 10½ in. (26.7 cm) thick limerock base. The RCA material constructed at test sections was delivered from the stockpiles of I-4 roadway slabs. All test sections were covered by 4 in. (20.2 cm) of FDOT specified S-1 asphalt concrete paved by Orlando Paving Company in Orlando, FL.

5.5 Test Section Construction

5.5.1 Removal of Track Slab

Before the construction of the new test sections, it was necessary to remove the existing concrete slab from the previous project. To perform this task a private company (Hunter Concrete) was contracted. The contractor excavated the test track and surrounding area with a backhoe and exposed a 10 in. (25.4 cm) existing concrete slab as seen in Photograph 5.1. Photograph 5.2, shows that a jackhammer was utilized to break up the concrete slab into pieces. The chunks of concrete rubble were deposited in a dumpster and hauled away to a local concrete recycling plant. In order to protect the existing bridge abutments, it was decided to remove the slab starting approximately 3 ft from the bridge abutment. The extraction of the half-track concrete slab was completed in three days.

Photograph 5.1 Excavating operation.



Photograph 5.2 Concrete Slab Section being cut using a Jack Hammer.

5.5.2 Compaction of Base Materials

Once the existing concrete slab was removed, the base materials used in the last project were also removed. The exposed ground level was then designated as the top of the subgrade layer. This subgrade layer consisted of soils from the existing fine sand at the bottom of the layer and the transported fine sand at the top. These soils fell in to the AASHTO A-3 material classification (51% minimum passing #40 sieve and 10% maximum passing #200 sieve).

The RCA and limerock materials were then placed on top of the sub-grade. The RCA was placed on sections 1 and 2, while limerock was placed on section 3. Photograph 5.3 shows the placement of RCA on the track using a backhoe, while Photograph 5.4 shows the spreading of RCA on the track by shovel and rakes. The compaction of base materials was done in three equal lifts for all test sections. Each lift was compacted by a 1,000 lb. (454 kg) vibrating compactor used by the contractor. Photograph 5.5 shows watering of the base material during compaction, while Photograph 5.6 shows the compacted area with a compactor. The final compacted RCA base on sections 1 and 2 are shown on Photograph 5.7.

After the compaction, Raad and Tannons Engineering Group, Inc., a local Geotechnical firm, conducted a Nuclear Gauge test to measure the moisture content and the dry density. The average moisture content and dry density of these base materials (RCA and limerock) were found to be 17.8% and 112.0 lb/ft^3 respectively. The dry density was close to the average values of laboratory compaction shown in Table 4.21.

Photograph 5.3 Placement of RCA by Backhoe.

Photograph 5.4 Spreading of RCA.

Photograph 5.5 Watering of Material During Compaction.

Photograph 5.6 Compacting RCA Base Course.

Photograph 5.7 Finished RCA Base Course (Sections 1 & 2).

5.5.3 The Asphalt Concrete Pavement Placement

In May 2000, a contractor from Central Asphalt Seal coating performed the initial asphalt pavement work. Later, when a Falling Weight Deflectometer (FWD) test was conducted on the test sections, it was discovered that the asphalt concrete surface was extremely soft. Since the pavement was incapable of carrying any load applications, the surface course was then removed. Subsequently, Orlando Paving Company (OPC) was contracted to place new asphalt concrete on August 19, 2000.

With the base courses in place, a crew from the Orlando Paving Company applied a prime coat to the surfaces in preparation for the hot mix asphalt (HMA). Once the prime coat had cured, a 15-man crew working with a paver, roller compactor, and other equipment, applied a 4 in. (10.2 cm) layer of HMA over the base course in three equal lifts. Each lift was compacted by a dual steel wheel roller compactor. After the placement of the HMA, several cores were cut from the pavement in order to test the properties of the HMA.

The following pictures (Photographs 5.9 through 5.16) illustrate the equipment and procedures used by the Orlando Paving Company for the construction of the pavement. Photograph 5.17 shows the finished surface of the test sections, while Photograph 5.18 shows the identification of the two RCA and the limerock test sections.

Photograph 5.9 Steel Wheel Roller for HMA Compaction

Photograph 5.10 Asphalt Paver

Photograph 5.11 Traffic Roller.

Photograph 5.12 Base Course Surface Cleaning.

Photograph 5.13 Application of The Primer Coat.

Photograph 5.14 Asphalt Layout by Paver.

Photograph 5.15 Spreading Asphalt.

Photograph 5.16 Asphalt Compaction.

Photograph 5.17 Finishing Surface.

Photograph 5.18 Test Section Identification.

5.6 Performance Test

The wheel load applied by the UCF-CATT machine represents the Florida legal axle load of 22,000 lbs. (98 kN), or a half axle of 11,000 lbs. (49 kN). Each tire carries as assumed equal load of 5,500 lbs. (24.5 kN) with tire pressure of approximately 110 psi (759 kPa). A total of 362,198 load repetitions were applied to the test sections. The time log of load application is presented in Appendix B. The life expectancy of these pavement systems for the total load application is analyzed in Chapter 6, Theoretical Analysis.

5.7 Distress Measurements

Pavement distresses were monitored during the course of performance testing. The distresses were measured for rutting, cracking, and settlement at the end of the performance test.

5.7.1 Rutting

Rutting was measured using a straight edge on the pavement surface. Photograph 5.19 shows the rutting measurements. No rutting was observed in any of the test sections except the surface wear directly under the wheel path. This was supported by surface level measurements between the outside and the inside wheel paths. The surface wear was simply due to the excessive abrasion of the tires.

5.7.2 Cracking

A total of 16 transverse cracks and one longitudinal crack appeared along the wheel path in the limerock section. The longitudinal crack occurred at the end of the test section. It measured approximately 35 in. (90cm) long. The transverse cracks varied from 10 in. (25cm) to 31 in. (80cm) in length. The largest transverse crack was measured approximately 1/8 in. (0.3cm) in width. Some of the transverse cracks in the limerock test section are shown in Photograph 5.20. No cracks were observed in either RCA test section.

5.7.3 Settlement

Two distinct settlements, both of which occurred at the test section ends where connected to the two bridge decks. The settlement was obviously due to a lack of full compaction caused by the concrete slab blocking the compacting energy. The settlement in the limerock section was measured to be 1¾ in. (4.5cm) as compared to ¾ in. (2.0cm) in the RCA section. Photograph 5.21.shows the settlement at the end of limerock test section.

Photograph 5.19 The Rutting Measurements in Test Sections.


April 03, 2001

360,000.00 Load Repetitions

Photograph 5.20 The Transverse Cracks on the Limerock Test Section.

Photograph 5.21 The Settlement at The End of Limerock Test Section.

CHAPTER 6

THEORETICAL ANALYSIS

The theoretical analysis was performed in order to model and predict the behavior of the test sections placed at the UCF-CATT. The analysis will compute the projected number of load repetitions, failures of fatigue and permanent deformation in the test sections. This estimate of the number of repetitions was then used to calculate the life expectancy of pavement test sections.

The theoretical analysis was performed in three stages. The first stage determined the deflection basins of the test sections generated by different loads from the Falling Weight Deflectometer (FWD) test. The second stage utilized the KENLAYER computer program (Huang, 1993) to estimate the in-situ material properties of the base, and subgrade materials by back-calculating the deflections to match FWD measured deflections. The third stage applied the same program using the properties of the pavement components to calculate the strains at the critical positions under the given wheel load of 11,000 lbs (48.9 KN). The results are used to predict the failure criteria.

6.1 Falling Weight Deflectometer Test

The Falling Weight Deflectometer (FWD) is a device that can deliver transient force impulses to pavement surfaces (see Photograph 6.1). The FWD test is a non-destructive test method that measures pavement deflection.

FDOT staff performed the first FWD test at the UCF-CATT test sections on 8/25/2000. The transducers were located at 8 in. (20.32 cm), 12 in. (30.48 cm), 18 in. (45.72 cm), 24 in. (60.96 cm), 36 in. (91.44 cm) and 60 in. (152.4 cm) from the center of the plate respectively. Three dynamic loads were applied to each test section at four different locations by using the same weight but varying the height of the drop. The magnitude of the load measured by the load cell ranged between 79 psi (550 kPa) to 134 psi (925 kPa). Figure 6.1 presents the schematic diagram of the test sections and the locations of the weight drop from FWD.

Photograph 6.1 Falling Weight Deflectometer Test

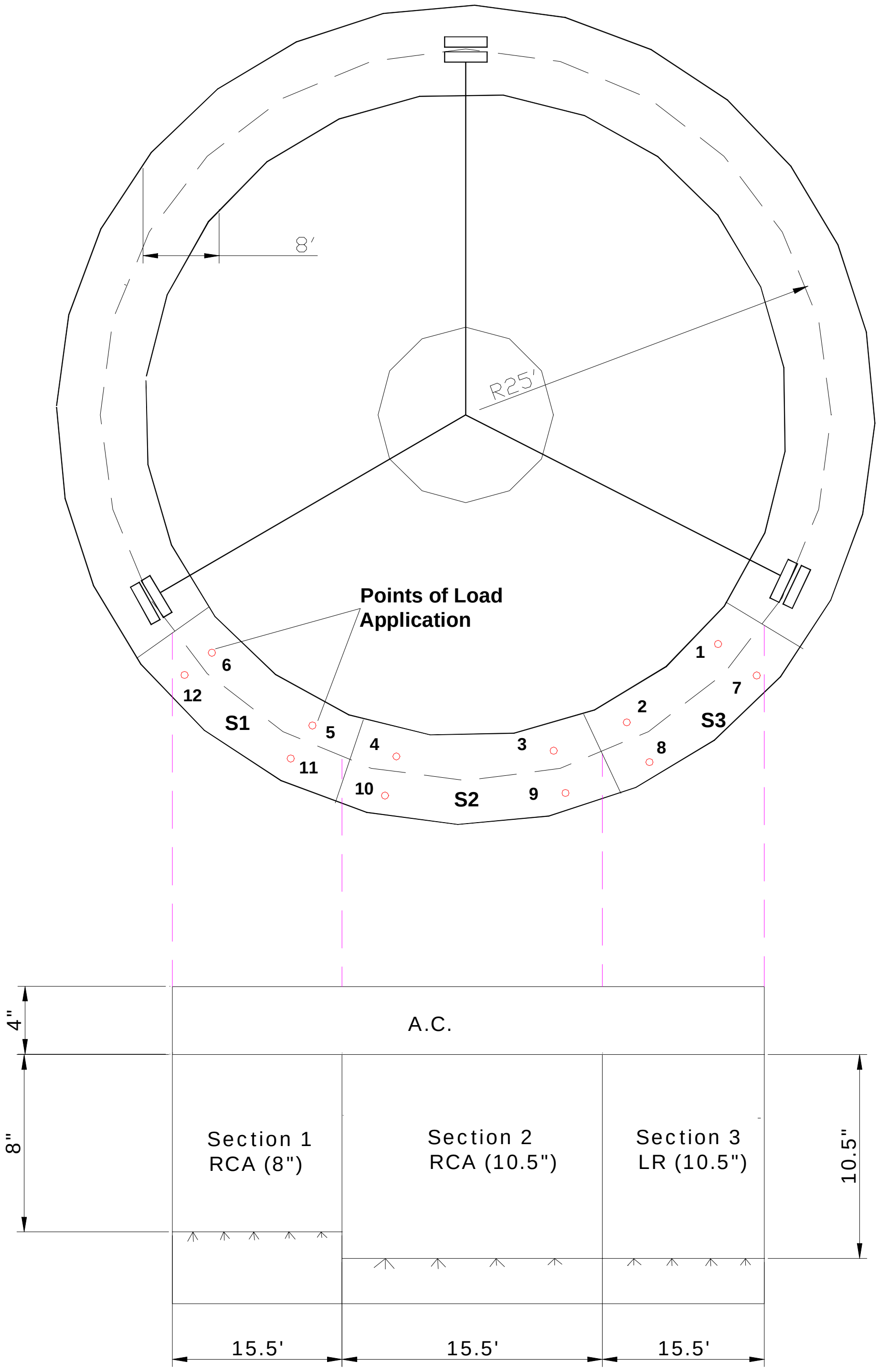


Figure 6.1 Position of FWD Test on Test Sections

The results of the FWD test are presented in Tables 6.1 through 6.3. The average deflection data given in the table are the mean value of deflections taken at the four locations for each load range. These average values were used to plot deflection basins for each test section. Figures 6.2 through 6.4 show the deflection basins for test sections 1,2, and 3 respectively. As seen from each figure, it is apparent that the higher load range by FWD produces a higher deflection value. By comparing the deflection data either from the tables or from the figures of deflection basins, it is interesting to see that every deflection measured in the limerock test section is significantly higher than those in the RCA test sections, while the deflections between the two RCA test sections show practically no difference. In fact, the deflection basins between the two RCA test sections nearly coincided. The FWD deflection data are presented in Appendix C.

Table 6.1 Average Deflections for a 8.0 in RCA Layer, Four Readings.

Deflection RCA. 8.0 in Section 1 (08/25/2000)								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S1T5	544.76	-0.2355	-0.1521	-0.1295	-0.1044	-0.0859	-0.0612	-0.0368
S1T6	544.28	-0.2720	-0.1593	-0.1328	-0.1054	-0.0846	-0.0612	-0.0358
S1T11	541.35	-0.2489	-0.1572	-0.1318	-0.1097	-0.0899	-0.0632	-0.0368
S1T12	545.74	-0.2593	-0.1562	-0.1308	-0.1074	-0.0879	-0.0612	-0.0368
Average	**544.03**	**-0.2539**	**-0.1562**	**-0.1313**	**-0.1067**	**-0.0871**	**-0.0617**	**-0.0366**

Deflection RCA. 8.0 in Section 1								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S1T5	733.02	-0.3200	-0.2083	-0.1775	-0.1427	-0.1168	-0.0841	-0.0500
S1T6	729.60	-0.3670	-0.2195	-0.1829	-0.1458	-0.1179	-0.0841	-0.0480
S1T11	731.55	-0.3388	-0.2154	-0.1816	-0.1509	-0.1250	-0.0861	-0.0500
S1T12	734.97	-0.3526	-0.2144	-0.1786	-0.1478	-0.1209	-0.0841	-0.0500
Average	**732.28**	**-0.3446**	**-0.2144**	**-0.1801**	**-0.1468**	**-0.1201**	**-0.0846**	**-0.0495**

Deflection RCA. 8.0 in Section 1								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S1T5	918.83	-0.4122	-0.2715	-0.2327	-0.1882	-0.1529	-0.1090	-0.0643
S1T6	915.90	-0.4696	-0.2870	-0.2390	-0.1933	-0.1539	-0.1090	-0.0622
S1T11	914.93	-0.4331	-0.2797	-0.2370	-0.1976	-0.1623	-0.1120	-0.0643
S1T12	922.73	-0.4572	-0.2807	-0.2360	-0.1933	-0.1590	-0.1110	-0.0643
Average	**918.10**	**-0.4430**	**-0.2797**	**-0.2362**	**-0.1931**	**-0.1570**	**-0.1102**	**-0.0638**

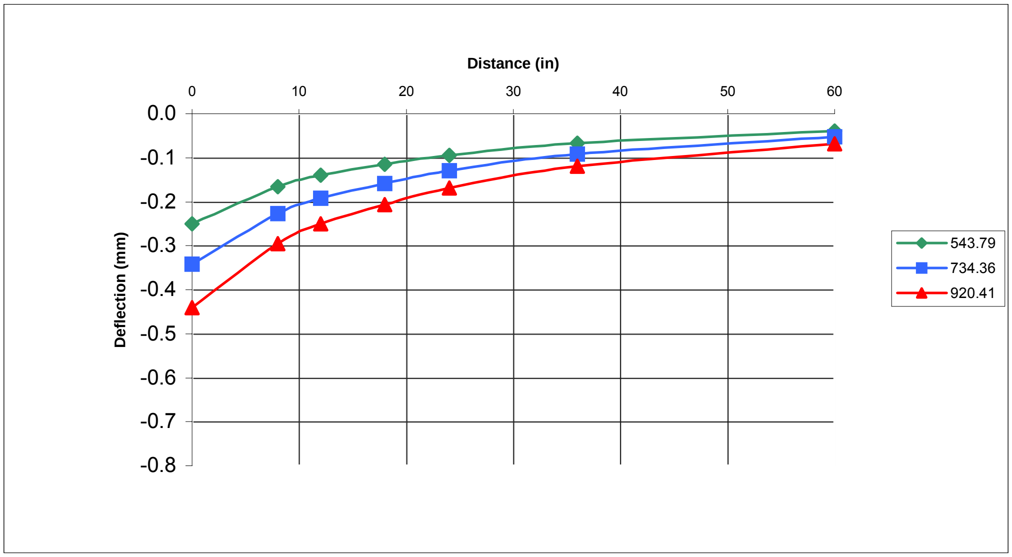


Figure 6.2 Average Deflections for a 8.0 in RCA Layer Section 1 (08/25/2000)

Table 6.2 Average Deflections for a 10.5 in RCA Layer, Four Readings.

Deflection RCA. 10.5 in Section 2 (08/25/2000)

Sect#	Load	Distance from the Applied Load (in)						
Test#	(KPa)	0	8	12	18	24	36	60
S2T3	547.69	-0.2583	-0.1715	-0.1450	-0.1189	-0.0970	-0.0696	-0.0409
S2T4	544.28	-0.2322	-0.1562	-0.1339	-0.1085	-0.0879	-0.0643	-0.0389
S2T9	544.28	-0.2563	-0.1725	-0.1461	-0.1219	-0.1001	-0.0716	-0.0409
S2T10	538.91	-0.2553	-0.1623	-0.1349	-0.1097	-0.0909	-0.0632	-0.0368
Average	**543.79**	**-0.2505**	**-0.1656**	**-0.1400**	**-0.1147**	**-0.0940**	**-0.0672**	**-0.0394**

Deflection RCA. 10.5 in Section 2

Sect#	Load	Distance from the Applied Load (in)						
Test#	(KPa)	0	8	12	18	24	36	60
S2T3	737.89	-0.3515	-0.2360	-0.2002	-0.1643	-0.1334	-0.0955	-0.0551
S2T4	733.99	-0.3160	-0.2144	-0.1829	-0.1478	-0.1219	-0.0871	-0.0521
S2T9	733.99	-0.3536	-0.2360	-0.2002	-0.1674	-0.1374	-0.0975	-0.0551
S2T10	731.55	-0.3482	-0.2215	-0.1859	-0.1519	-0.1250	-0.0871	-0.0500
Average	**734.36**	**-0.3423**	**-0.2269**	**-0.1923**	**-0.1579**	**-0.1294**	**-0.0918**	**-0.0531**

Deflection RCA. 10.5 in Section 2

Sect#	Load	Distance from the Applied Load (in)						
Test#	(KPa)	0	8	12	18	24	36	60
S2T3	923.22	-0.4488	-0.3053	-0.2604	-0.2141	-0.1735	-0.1245	-0.0706
S2T4	920.78	-0.4079	-0.2786	-0.2390	-0.1943	-0.1590	-0.1140	-0.0676
S2T9	920.29	-0.4602	-0.3073	-0.2624	-0.2192	-0.1808	-0.1265	-0.0706
S2T10	917.37	-0.4445	-0.2870	-0.2410	-0.1976	-0.1623	-0.1130	-0.0643
Average	**920.41**	**-0.4404**	**-0.2946**	**-0.2507**	**-0.2063**	**-0.1689**	**-0.1195**	**-0.0683**

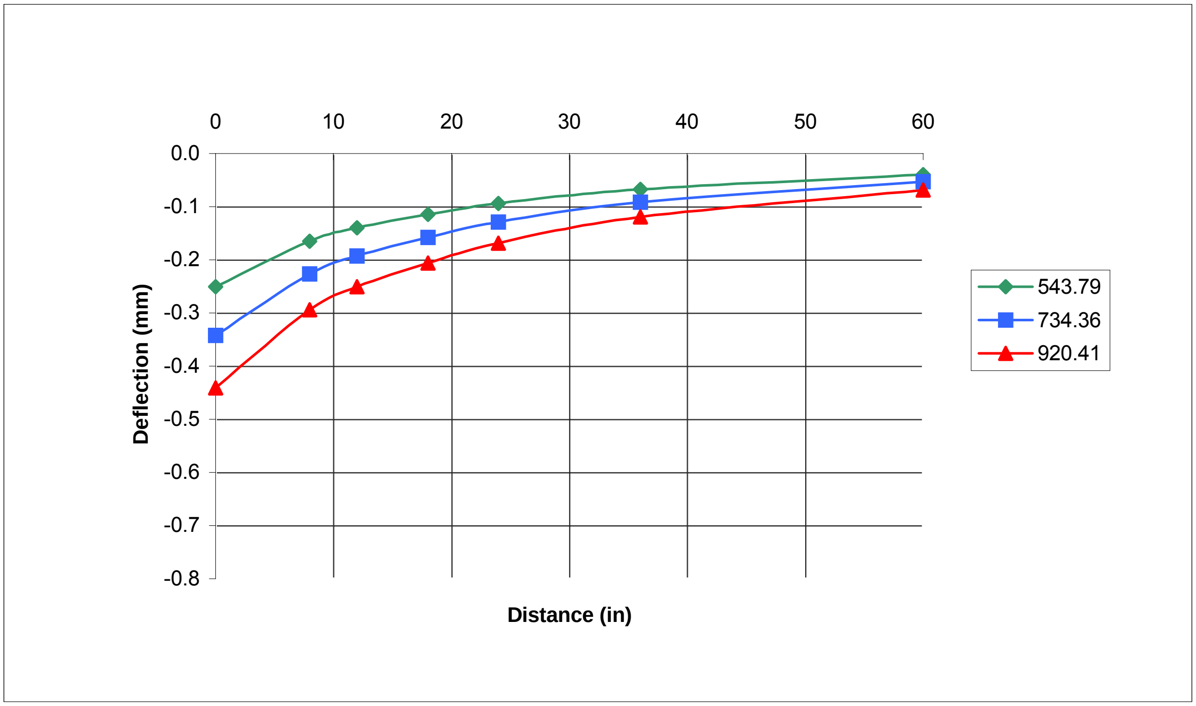


Figure 6.3 Average Deflections for a 10.5 in RCA Layer Section 2 (08/25/2000)

Table 6.3 Average Deflection for Lime Rock at Control Section, Four Readings.

Deflection L.R. 10.5 in Section 3 (08/25/2000)								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S3T1	549.64	-0.3703	-0.2154	-0.1613	-0.1168	-0.0909	-0.0632	-0.0389
S3T2	539.89	-0.3566	-0.2113	-0.1582	-0.1168	-0.0919	-0.0653	-0.0389
S3T7	539.40	-0.3945	-0.2266	-0.1694	-0.1242	-0.0950	-0.0663	-0.0409
S3T8	544.28	-0.3056	-0.1991	-0.1532	-0.1148	-0.0909	-0.0663	-0.0399
Average	**543.30**	**-0.3567**	**-0.2131**	**-0.1605**	**-0.1182**	**-0.0922**	**-0.0653**	**-0.0396**

Deflection L.R. 10.5 in Section 3								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S3T1	734.48	-0.4696	-0.2827	-0.2144	-0.1572	-0.1219	-0.0861	-0.0531
S3T2	727.65	-0.4895	-0.2901	-0.2195	-0.1613	-0.1260	-0.0881	-0.0521
S3T7	727.16	-0.5334	-0.3094	-0.2316	-0.1697	-0.1300	-0.0912	-0.0551
S3T8	734.48	-0.4331	-0.2705	-0.2093	-0.1572	-0.1250	-0.0902	-0.0541
Average	**730.94**	**-0.4814**	**-0.2882**	**-0.2187**	**-0.1614**	**-0.1257**	**-0.0889**	**-0.0536**

Deflection L.R. 10.5 in Section 3								
Sect#	**Load**	**Distance from the Applied Load (in)**						
Test#	**(KPa)**	**0**	**8**	**12**	**18**	**24**	**36**	**60**
S3T1	918.34	-0.6078	-0.3594	-0.2746	-0.2027	-0.1580	-0.1110	-0.0686
S3T2	911.51	-0.6297	-0.3777	-0.2880	-0.2131	-0.1643	-0.1140	-0.0676
S3T7	910.54	-0.6904	-0.4013	-0.3023	-0.2212	-0.1684	-0.1181	-0.0716
S3T8	918.83	-0.5763	-0.3513	-0.2736	-0.2047	-0.1623	-0.1161	-0.0696
Average	**914.81**	**-0.6260**	**-0.3724**	**-0.2846**	**-0.2104**	**-0.1633**	**-0.1148**	**-0.0693**

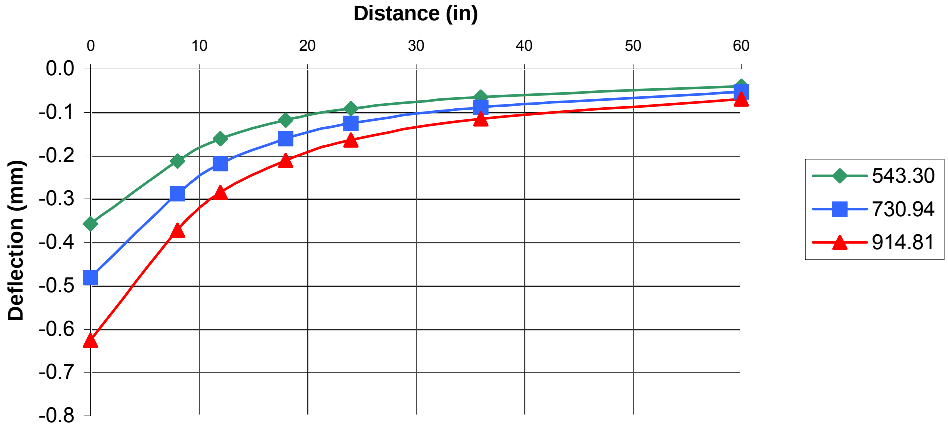


Figure 6.4 Average Deflections for Lime Rock Layer Section 3 (08/25/2000)

6.2 Back-Calculation of In-Situ Elastic Modulus Using KENLAYER

One of the useful applications of non-destructive testing (NDT) is to back-calculate the in situ moduli of pavement components, including the subgrade. The procedure is based on measuring the deflection basin by varying the set of moduli until a best match between the computed and measured FWD deflection is obtained. KENLAYER (Huang, 1992) is a flexible pavement computer program. The program is capable of examining circular loaded areas (single, dual, dual-tandem, or dual-tridem wheels) on multi-layered pavement systems that are linear elastic, non-linear elastic, or visco-elastic behavior.

The KENLAYER program was employed to back-calculate the modulus of elasticity of the RCA base material by using the load-deflection data obtained from the FWD test. Figure 6.5 depicts the diagram of wheel load and pavement cross section for input parameters in KENLAYER.

The resilient modulus of HMA surface course was determined from the laboratory cyclic load testing conducted by University of Florida based on four core samples from the test section. The resilient modulus results for the four samples are: 372,000 psi (53,952 kPa), 510,000 psi (73,967 kPa), 400,000 psi (58,013 kPa), and 364,000 psi (52,792 kPa), respectively. An average modulus of 380,000psi (55,112 kPa) is used for the input of surface course in KENLAYER. The detail of the test data is presented in Appendix D.

After trial and error with numerous combinations of the base and subgrade modulus values, the moduli of the base and subgrade layers as bonded pavement components for the best fit of deflection basins were found to be E_{RCA}=195,000psi (28,281 kPa), E_{LR}=60,000 psi (8,702 kPa), and E_{Subg}=30,000 psi (4,350 kPa). The resilient modulus of RCA obtained from this analysis is comparable to the results of the Test Pit conducted by FDOT Materials Office in Gainesville (Boatman, 1999).

Figures 6.6 through 6.14 present the best-fit curves from the FWD deflection basins and the KENLAYER program. Tables 6.4 through 6.6 present the comparison of deflection values between the FWD test and the KENLAYER outputs for the sections 1, 2, and 3, respectively. Appendix E provides the samples of KENLAYER printouts on test sections 1 and 2.

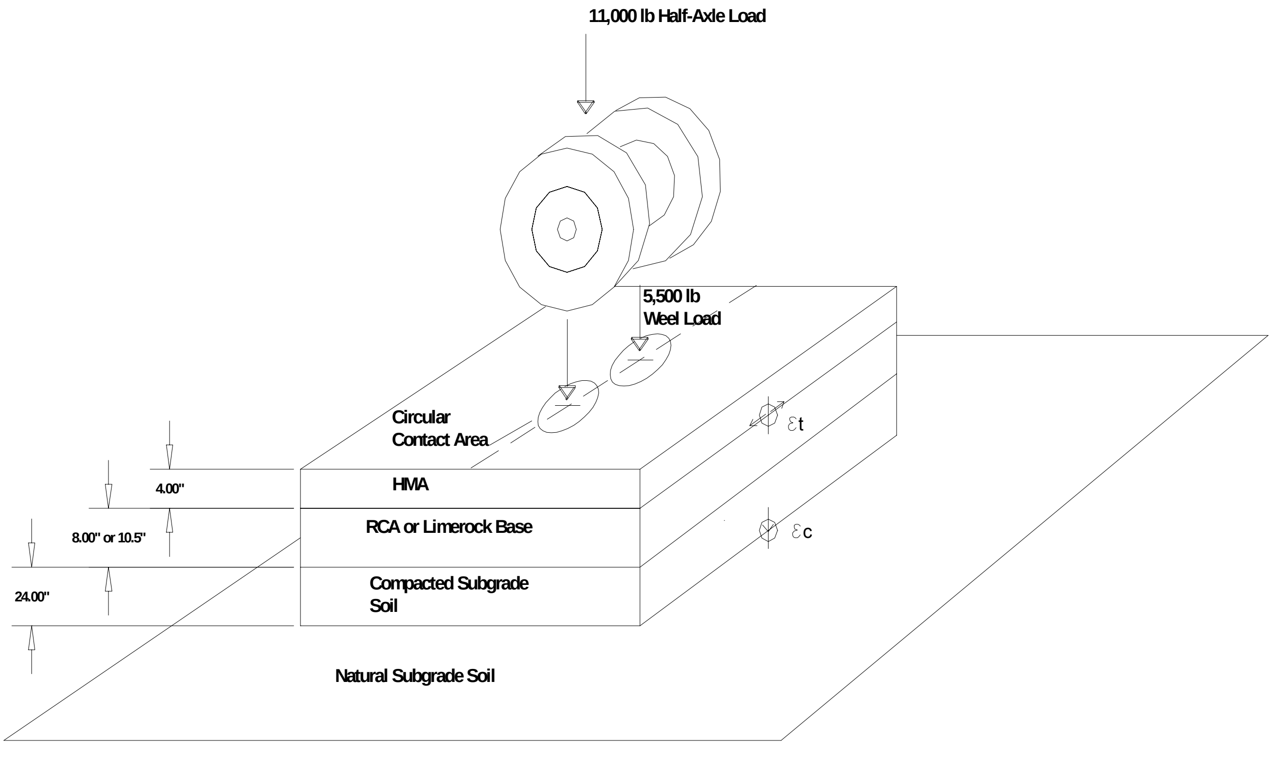


Figure 6.5 Wheel Load and Pavement Cross Section for Kenlayer Input

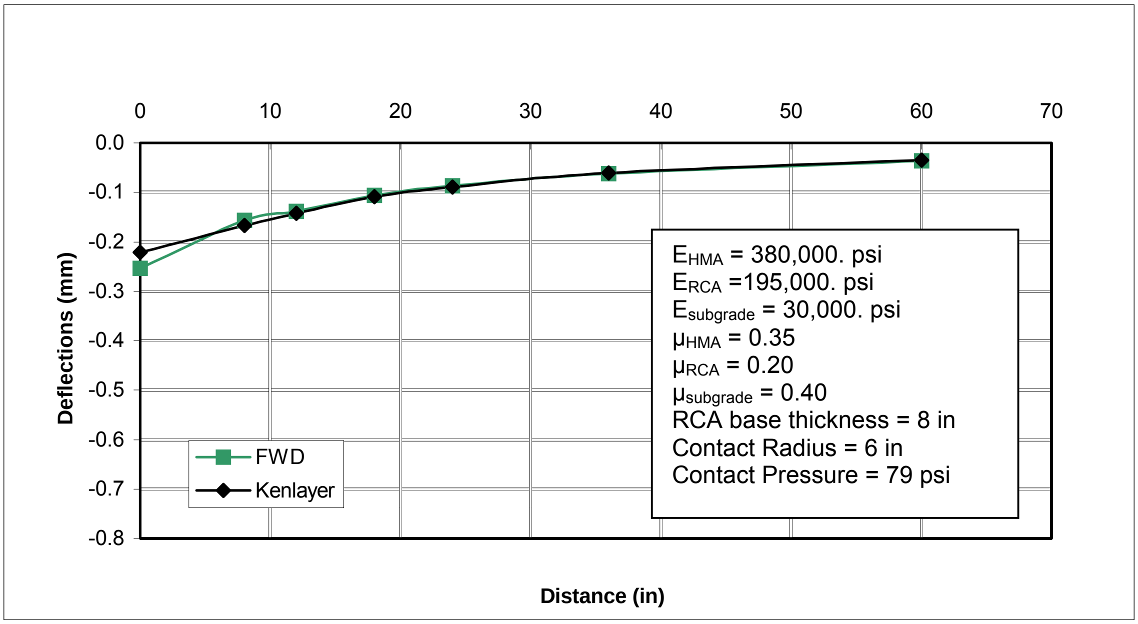


Figure 6.6 Comparison of Kenlayer and FWD at a Contact Pressure of 544 kPa (Section 1)

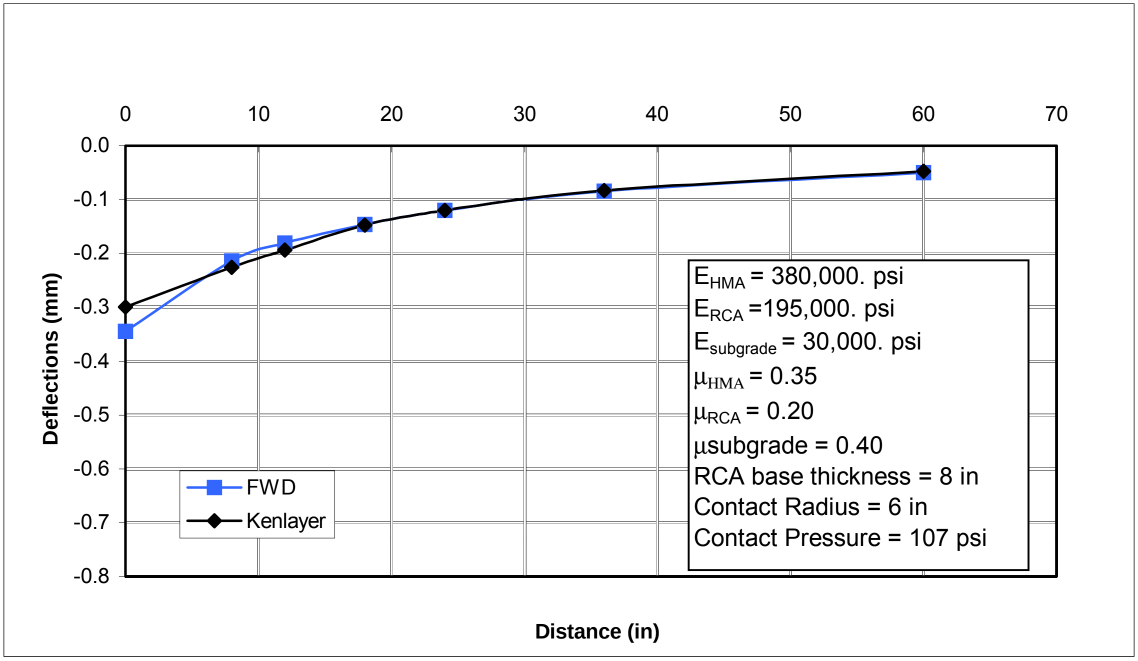


Figure 6.7 Comparison of Kenlayer and FWD at a Contact Pressure of 734 kPa(Section 1)

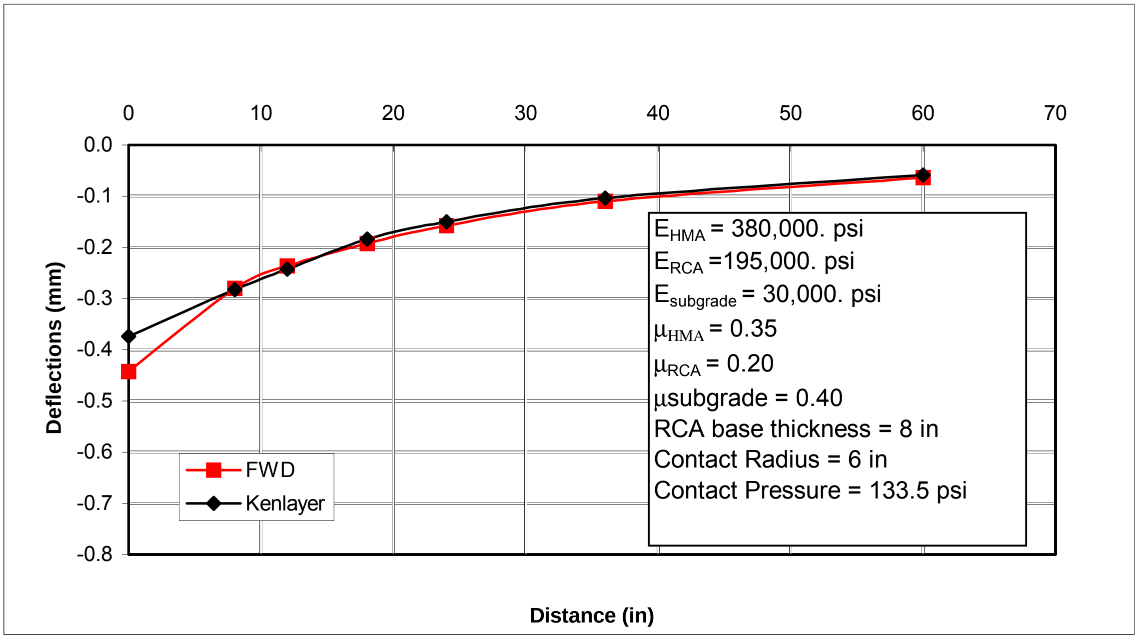


Figure 6.8 Comparison of Kenlayer and FWD at a Contact Pressure of 920 kPa (Section 1)

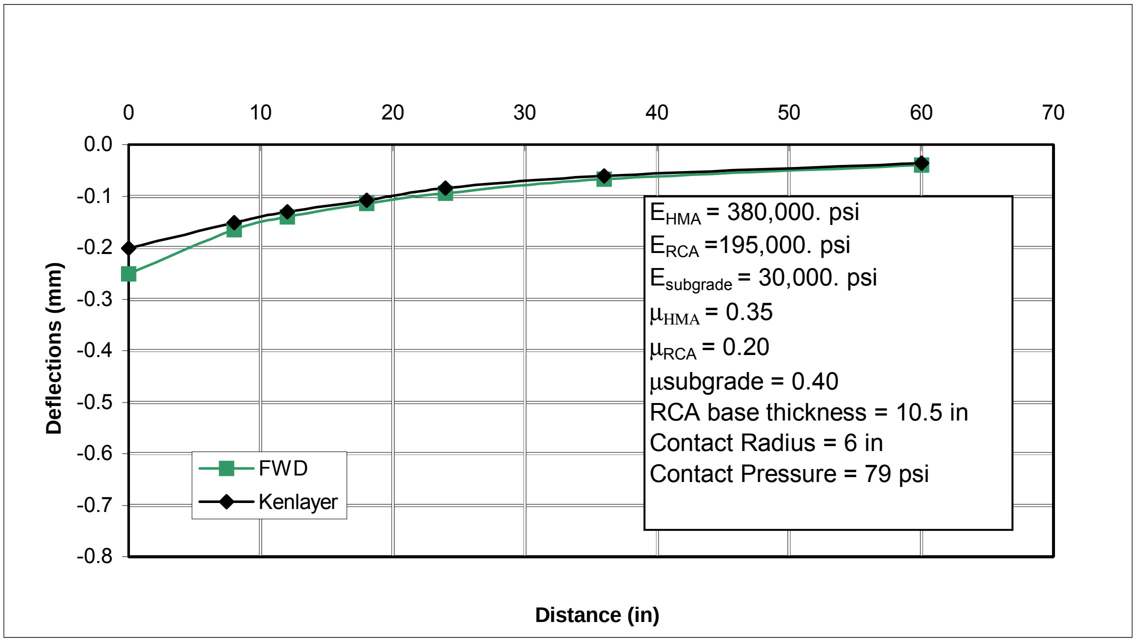


Figure 6.9 Comparison of Kenlayer and FWD at a Contact Pressure of 544 kPa (Section 2)

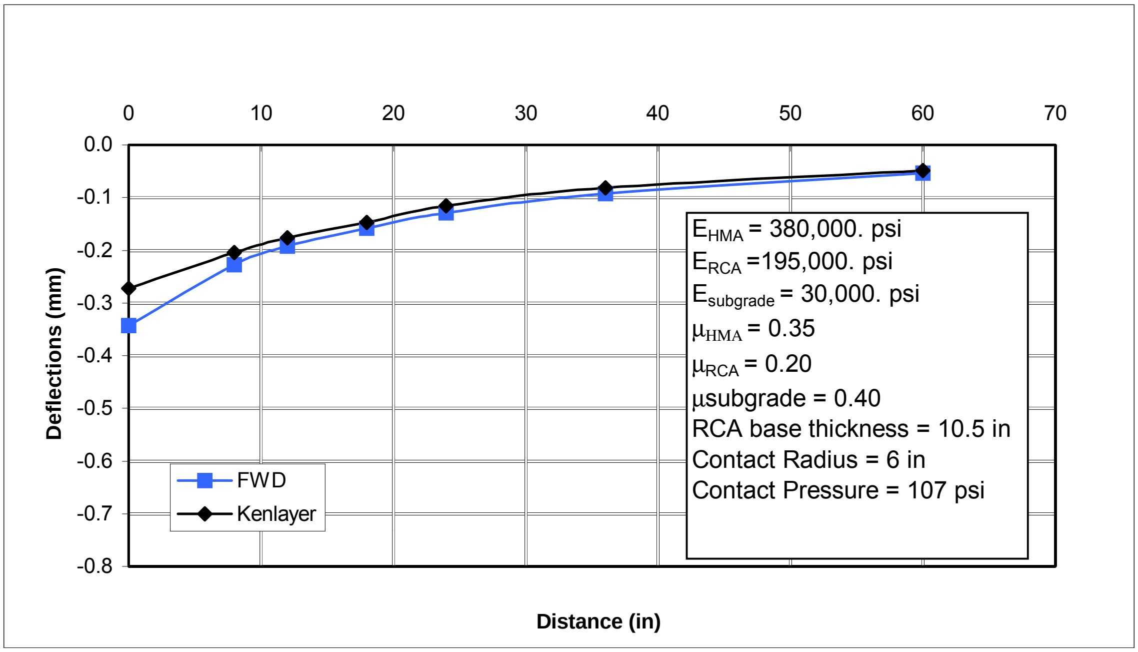


Figure 6.10 Comparison of Kenlayer and FWD at a Contact Pressure of 734 kPa(Section 2)

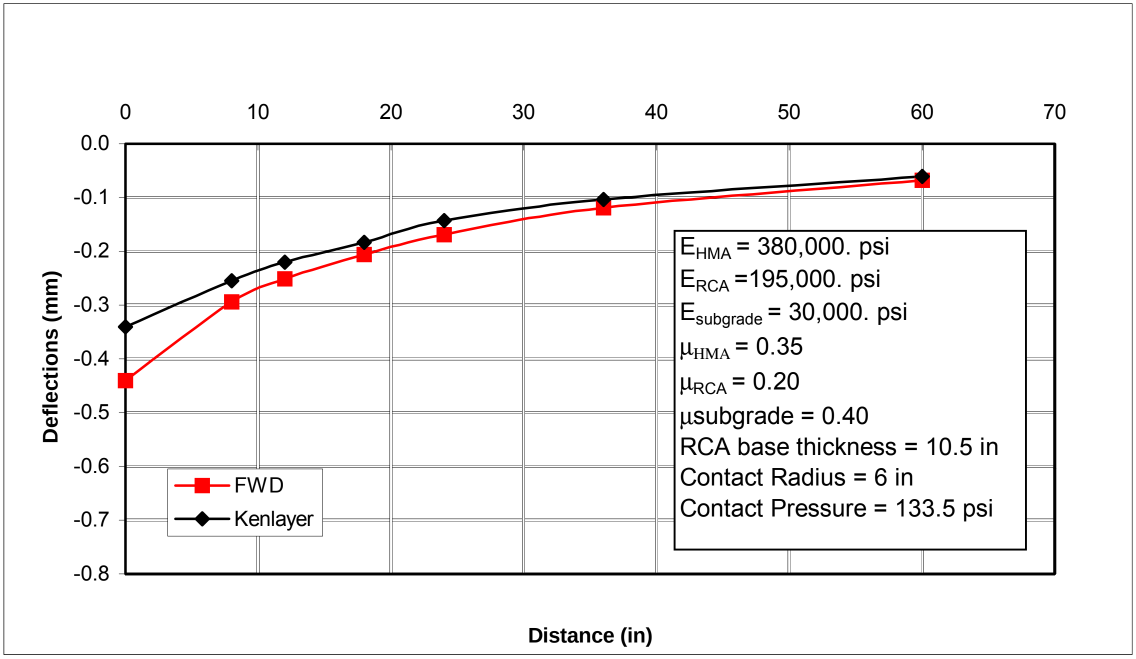


Figure 6.11 Comparison of Kenlayer and FWD at a Contact Pressure of 920 kPa(Section 2)

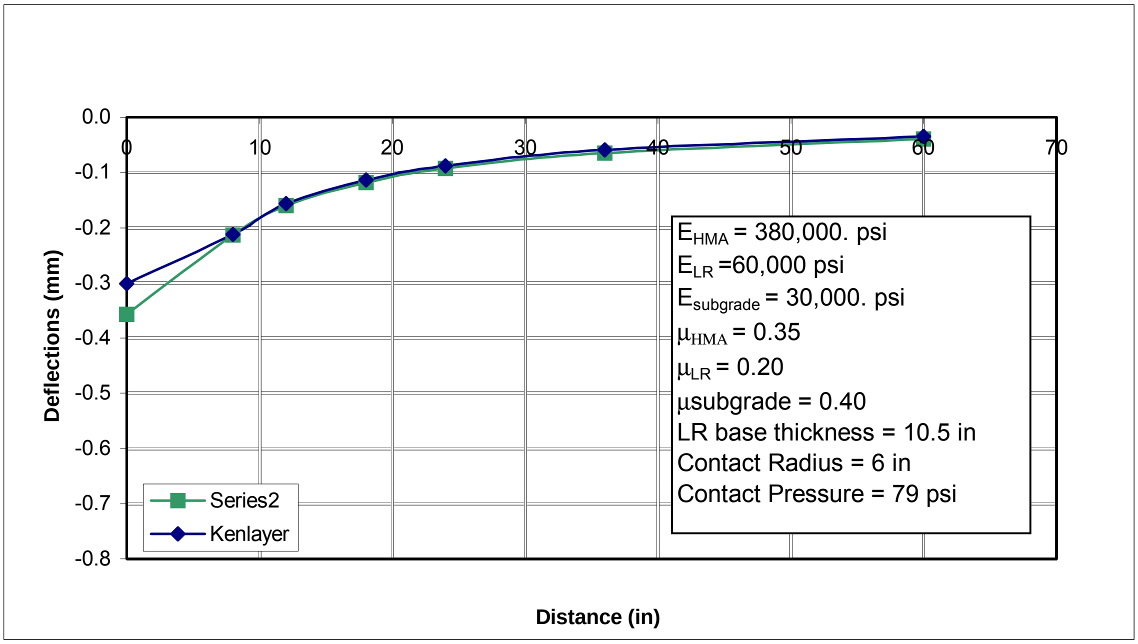


Figure 6.12 Comparison of Kenlayer and FWD at a Contact Pressure of 544 kPa (Section 3)

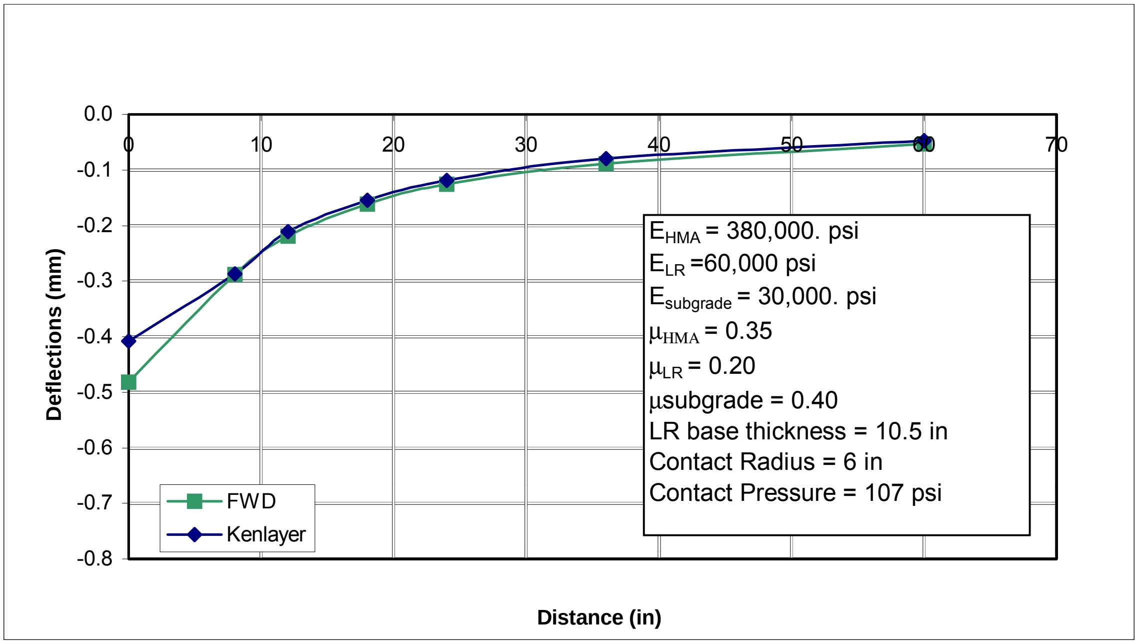


Figure 6.13 Comparison of Kenlayer and FWD at a Contact Pressure of 734 kPa (Section 3)

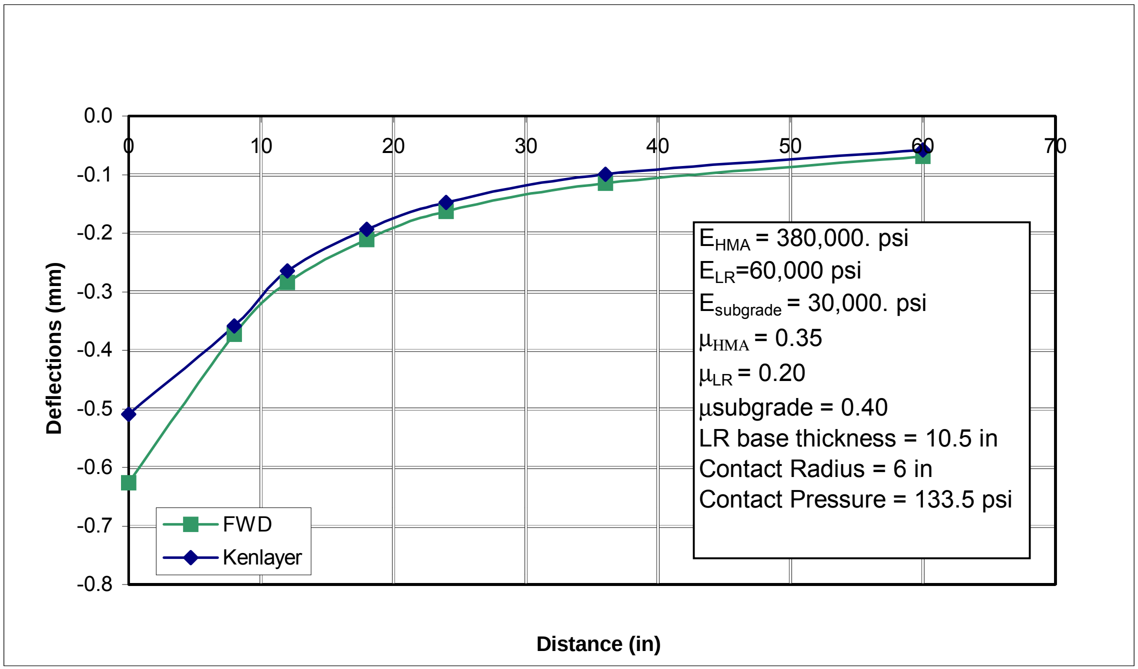


Figure 6.14 Comparison of Kenlayer and FWD at a Contact Pressure of 920 kPa (Section 3)

Table 6.4. Comparison of Deflections between FWD Test and KENLAYER Outputs for Section 1

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
FWD	543.79	-0.2539	-0.1567	-0.1380	-0.1067	-0.0871	-0.0617	-0.0366
Kenlayer	544.71	-0.2210	-0.1670	-0.1430	-0.1090	-0.0890	-0.0610	-0.0350
FWD	734.36	-0.3446	-0.2144	-0.1801	-0.1468	-0.1201	-0.0846	-0.0495
Kenlayer	734.36	-0.3000	-0.2260	-0.1940	-0.1470	-0.1200	-0.0830	-0.0470
FWD	920.41	-0.4430	-0.2797	-0.2362	-0.1931	-0.1570	-0.1102	-0.0638
Kenlayer	920.41	-0.374	-0.2820	-0.242	-0.184	-0.15	-0.104	-0.059

Table 6.5 Comparison of Deflections between FWD Test and KENLAYER Outputs for Section 2

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
FWD	543.79	-0.2505	-0.1656	-0.1400	-0.1147	-0.0940	-0.0672	-0.0394
Kenlayer	544.70	-0.2010	-0.1510	-0.1300	-0.1080	-0.0850	-0.0610	-0.0360
FWD	734.36	-0.3423	-0.2269	-0.1923	-0.1579	-0.1294	-0.0918	-0.0531
Kenlayer	737.77	-0.2720	-0.2040	-0.1760	-0.1470	-0.1150	-0.0820	-0.0490
FWD	920.41	-0.4404	-0.2946	-0.2507	-0.2063	-0.1689	-0.1195	-0.0683
Kenlayer	920.48	-0.34	-0.255	-0.22	-0.183	-0.143	-0.103	-0.061

Table 6.6 Comparison of Deflections between FWD Test and KENLAYER Outputs for Section 3

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
FWD	543.79	-0.3567	-0.2131	-0.1605	-0.1182	-0.0922	-0.0653	-0.0396
Kenlayer	544.70	-0.301	-0.212	-0.156	-0.114	-0.088	-0.059	-0.035
FWD	734.36	-0.4814	-0.2882	-0.2187	-0.1614	-0.1257	-0.0889	-0.0536
Kenlayer	737.77	-0.408	-0.287	-0.211	-0.154	-0.119	-0.08	-0.047
FWD	920.41	-0.6260	-0.3724	-0.2846	-0.2104	-0.1633	-0.1148	-0.0693
Kenlayer	920.48	-0.509	-0.358	-0.264	-0.193	-0.148	-0.1	-0.058

6.3 Failure Criteria of Flexible Pavements

The theoretical failure criteria of flexible pavements are fatigue cracking and permanent deflection (rutting). The equations of fatigue and rutting criteria (Craus et. al. 1984) are proposed by the Asphalt Institute and other agencies as:

$$N_f = f_1 * (\epsilon_t)^{-f2} (E_1)^{-f3} \qquad (6.1)$$

$$N_d = f_4 * (\epsilon c)^{-f5} \qquad (6.2)$$

Where N_f = Number of allowable load repetitions to prevent fatigue.
ϵ_t = Tensile strain at the bottom of the asphalt layer.
E_1 = Elastic modulus of asphalt concrete.
$f_{1,} f_{2,} f_3$ = Constants determined from laboratory fatigue tests.
N_d = Number of allowable load repetitions to limit permanent deformation.
ϵ_c = Compressive strain on top of subgrade.
$f_{4,} f_{5,}$ = Constants determined from road test or road performance.

Table 6.7 lists the constants of criteria recommended by the Asphalt Institute.

Table 6.7 Recommended Constant Values by the Asphalt Institute

Constant	Asphalt Institute Value
f_1	0.0796
f_2	3.291
f_3	0.854
f_4	1.365×10^{-9}
f_5	4.477

The contact area for each load carrying 5,500 lbs. (24.5 kN) with a tire pressure of 110 psi (759 kPa) is calculated by the formula:

$$\text{Radius} = \{(\text{Wheel Load} / \text{Tire Pressure}) / \pi\}^{1/2} \qquad (6.3)$$

The contact radius for each tire load applied at the UCF-CATT was 3.99in. (101 mm) as shown in Figure 6.5.

By transferring the known input data of wheel load, tire contact area, layer dimensions, modulus of each layer to the KENLAYER program, the tensile strain at the bottom of the asphalt layer, and the compressive strain on the top of subgrade were calculated. The results are presented in Table 6.8.

Table 6.8. Computed Tensile Strain and Compressive Strain for Sections 1,2 and 3

Test Section	Tensile Strain (ϵ_t)	Compressive Strain (ϵ_c)
Section 1	0.8135×10^{-4}	0.4191×10^{-3}
Section 2	0.7796×10^{-4}	0.3107×10^{-3}
Section 3	0.2549×10^{-4}	0.4491×10^{-3}

By applying E_1 and the data from Tables 6.7 and 6.8 in Equations 6.1 and 6.2, the computed N_f and N_d are given in Tables 6.9 and 6.10. These tables are used to compare the performance of the test sections at UCF-CATT.

Table 6.9. Number of Allowable Repetitions to Fatigue Failure

Test Section	N_f
Section 1	39.34×10^{6}
Section 2	45.30×10^{6}
Section 3	9.20×10^{5}

Table 6.10. Number of Allowable Repetitions to Rutting Failure

Test Section	N_d
Section 1	1.8×10^{6}
Section 2	6.9×10^{6}
Section 3	1.3×10^{6}

6.4 Life Expectancy Analysis

Pavement systems are subjected to a wide range of vehicles. To consider the number of load repetition for mixed traffic and evaluate its damage from different axle loads is considered a tedious task. For the design of pavement systems, a simplified and widely accepted procedure relies on converting each load group into an equivalent 18 kips (80 kN) single axle load as proposed by AASHTO. Huang (1993) states that an equivalent axle load factor defines the damage per pass to pavement by the axle in question relative to the damage per pass of a standard 18 kips (80 kN) single axle load. FDOT authorized single axle load of 22 kips (98 kN) for a Florida legal load truck. For the accelerated testing, the machine applied a dual wheel load of 11 kips (49kN). This dual wheel loading, which is equivalent to 22 kips (98kN) single axle load, is heavier than the standard 18 kips (80kN) single axle load. Therefore, it was necessary to convert the repetitions administered by the 22 kips (98kN) to an equivalent amount of repetitions produced by the standard 18 kips (80kN) equivalent single axle load (ESAL) as specified by AASHTO for a standard truck. An equivalent axle load factor (EALF) can either be defined by utilizing AASHTO's conversion tables from the 1994 manual, or by using Equation 6.4, which is based on the fatigue criterion concept. A 22 kips (98kN) $ESAL_{18}$ is defined by Equation 6.5.

$$\text{EALF} = \left(\frac{Lx}{18}\right)^{4.02} \tag{6.4}$$

$$ESAL_{18} = N_{22} \text{ X EALF} \tag{6.5}$$

Where EALF = Equivalent axle load factor

L_X = 22 kip. (98 kN) single axle load.

N_{22}. = The numbers of passes of the 22 kip (98 kN) load repetitions applied at the test track.

$ESAL_{18}$. = The numbers of 18 kip (80 kN) load corresponding to N_{22}.

The sum of the repetitions successfully completed at the UCF-CATT can be used to equate the tested paving materials simulated life expectancy (SLE) if it were applied to normal highway conditions. The SLE has been tailored to site-specific applications through the use of actual traffic volumes. Therefore, the actual yearly truck traffic must be evaluated. As an example, let's hypothetically take an average daily traffic (ADT) volume of 7,500 in one-direction for typical medium-heavy highway traffic with an average 6% of 18 kips (80 kN) truck. The annual volume of heavy trucks can be calculated as follows:

$$AHTT = ADT \times T \times L \times 365 \text{ days} \tag{6.6}$$

Where: ADT = average daily traffic.
T = Percentage of trucks in the ADT.
L = Lane distribution factor (0.9 for the multi-lane highways).
AHTT = Annual 18 kip (80 kN) heavy truck traffic.

Unlike actual field conditions, the test track applied the load over the same path during each revolution. Taking this into account, a probability of occurrence of three is assumed for the wheel run at the same path. This means every third dual wheel load covered the same path along the pavement. Equation 6.7 equates the test track results to a simulated one-year life expectancy.

$$AHTT = N \times EALF \times P \tag{6.7}$$

Where: N = Number of 22 kips (98 kN) load repetitions required per year.
EALF = Equivalent axle load factor (Equation 6.4).
AHTT = Annual 18 kip (80 kN) heavy truck traffic (Equation 6.6).
P = Probability of occurrence = 3.

The simulated life expectancy of the test sections can then be calculated using Equation6.8:

$$SLE = ESAL_{18} / N \tag{6.8}$$

Where: SLE = Simulated life expectancy.

Applying the above equations and the data collected at the UCF-CATT, the computed values from Equations 6.4 through 6.8 are obtained and shown in Table 6.11.

Table 6.11 Simulated Life Expectancy Analysis.

VARIABLE	EQUATION	OUTPUT
EALF	6.4	2.24
$ESAL_{18}$	6.5	811,324 Reps
AHTT	6.6	147,825 Trucks
N	6.7	21,998 Reps
SLE	6.8	36.9 years

6.5 Performance Test at UCF-CATT

As seen in Table 6.11, a total of 362,198 load repetitions completed at UCF test track is equivalent to 811,324 of 18 kips (80 kN) ESAL. The simulated life expectancy (SLE) is calculated to be 36.9 years based on Equation 6.8. This SLE is obviously dependent on the assumptions of 7,500 ADT and 6% of 18 kips (80 kN) truck traffic. Should the ADT and the percent truck be higher, the SLE would be lower. A SLE of 36.9 years signifies that a strong pavement system was built at the test track. The outcome of this analysis agrees with the high numbers of allowable load repetitions to failures in fatigue and rutting as listed in Tables 6.9 and 6.10.

6.6 Deflection Measurements After Performance Test

In order to compare the deflection of test sections before and after the performance test, FDOT staff performed the second Falling Weight Deflectometer (FWD) test at the end of the performance test. Due to the malfunction of FWD Sensor 4(18in. from applied load), the deflection readings by this sensor were discarded. The results of the second FWD test are presented in Tables 6.12 through 6.14. The deflection data given in the tables are the mean values of deflections taken at the four locations for each of the three load levels. These average values were used to plot deflection basins for each test section. Figures 6.15 through 6.17 show the deflection basins for test sections 1, 2, and 3 respectively.

The comparisons between the first and the second FWD tests are presented in Tables 6.15 through 6.17. Figures 6.18 through 6.26 further show the comparison of the two FWD tests along with the deflection basin computed by the KENLAYER program using the material characterizations back calculated from the first FWD test.

As expected, the deflections taken at the second FWD test are slightly lower than the first test since the pavement has been compressed by applying 362,198 load repetitions on the test track. The moduli of layer components in this case will increase slightly. Since the decrease of deflection basins has been relatively small, no attempts will be made to obtain the moduli by running KENLAYER program.

Table 6.12 Average Deflections for a 8.0 in RCA Layer, Four Readings.

Deflection RCA. 8.0 in Section 1 (05/15/2001)

Sect#	Load	Distance from the Applied Load (in)					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S1T5	498.86	-0.1300	-0.1090	-0.0920	-0.0670	-0.0510	-0.0310
S1T6	527.94	-0.1220	-0.1000	-0.0850	-0.0610	-0.0470	-0.0280
S1T11	574.39	-0.1400	-0.1190	-0.1000	-0.0730	-0.0540	-0.0330
S1T12	545.74	-0.1500	-0.1170	-0.0980	-0.0730	-0.0530	-0.0320
Average	**536.73**	**-0.1355**	**-0.1113**	**-0.0938**	**-0.0685**	**-0.0513**	**-0.0310**

Deflection RCA. 8.0 in Section 1

Sect#	Load	Distance from the Applied Load (in)					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S1T5	674.19	-0.1850	-0.1520	-0.1310	-0.0960	-0.0510	-0.0310
S1T6	707.11	-0.1740	-0.1410	-0.1220	-0.0900	-0.0670	-0.0400
S1T11	740.09	-0.1900	-0.1640	-0.1400	-0.1010	-0.0730	-0.0440
S1T12	719.73	-0.2090	-0.1740	-0.1340	-0.1080	-0.0830	-0.0420
Average	**710.28**	**-0.1895**	**-0.1578**	**-0.1318**	**-0.0988**	**-0.0685**	**-0.0393**

Deflection RCA. 8.0 in Section 1

Sect#	Load	Distance from the Applied Load (in)					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S1T5	895.05	-0.2440	-0.2040	-0.1760	-0.1280	-0.0950	-0.0560
S1T6	880.55	-0.2320	-0.1930	-0.1670	-0.1220	-0.0930	-0.0520
S1T11	888.29	-0.2530	-0.2130	-0.1840	-0.1340	-0.0980	-0.0560
S1T12	916.39	-0.2740	-0.2080	-0.1830	-0.1280	-0.0920	-0.0540
Average	**899.91**	**-0.2508**	**-0.2045**	**-0.1775**	**-0.1280**	**-0.0950**	**-0.0550**

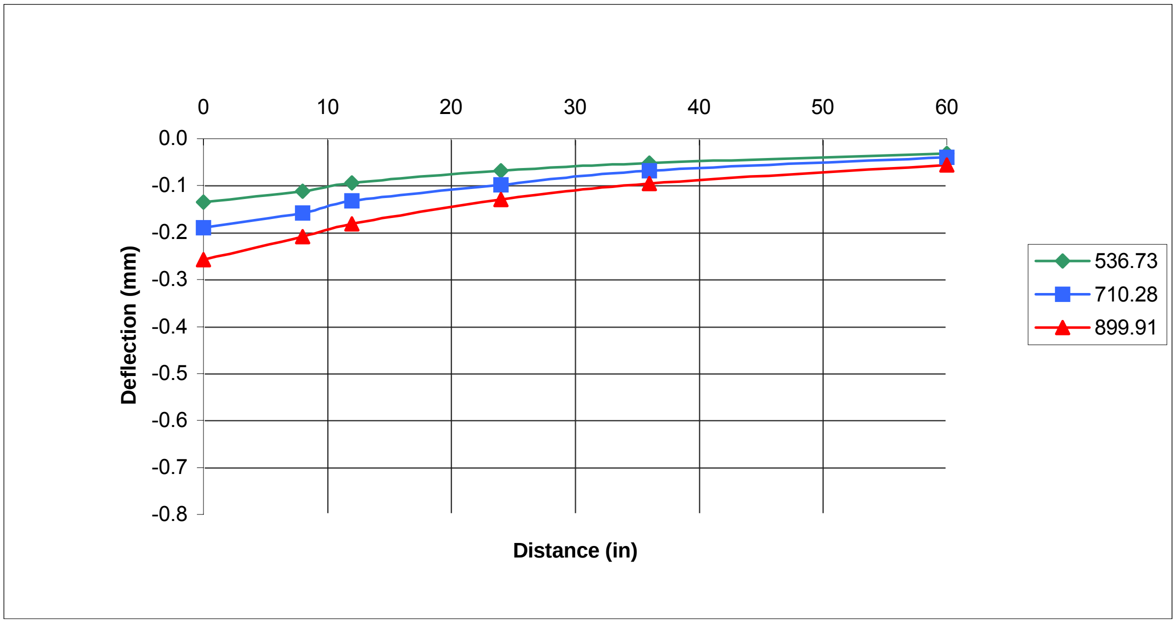


Figure 6.15 Average Deflections for a 8.0 in RCA Layer Section 1 (05/15/2001)

Table 6.13 Average Deflections for a 10.5 in RCA Layer, Four Readings.

Deflection RCA. 10.5 in Section 2 (05/15/2001)							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S2T3	495.93	-0.1370	-0.1130	-0.0970	-0.0730	-0.0560	-0.0330
S2T4	508.55	-0.1400	-0.1130	-0.0950	-0.0680	-0.0520	-0.0310
S2T9	527.94	-0.1560	-0.1130	-0.1000	-0.0790	-0.0610	-0.0360
S2T10	554.09	-0.1510	-0.1270	-0.1010	-0.0790	-0.0570	-0.0360
Average	**521.63**	**-0.1460**	**-0.1165**	**-0.0983**	**-0.0748**	**-0.0565**	**-0.0340**

Deflection RCA. 10.5 in Section 2							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S2T3	671.93	-0.2030	-0.1680	-0.1460	-0.1100	-0.0840	-0.0480
S2T4	693.57	-0.1970	-0.1600	-0.1370	-0.0990	-0.0750	-0.0440
S2T9	695.52	-0.2230	-0.1620	-0.1430	-0.1130	-0.0860	-0.0490
S2T10	706.13	-0.2140	-0.1730	-0.1440	-0.1070	-0.0790	-0.0470
Average	**691.79**	**-0.2093**	**-0.1658**	**-0.1425**	**-0.1073**	**-0.0810**	**-0.0470**

Deflection RCA. 10.5 in Section 2							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S2T3	892.13	-0.2740	-0.2300	-0.2000	-0.1510	-0.1150	-0.0650
S2T4	892.13	-0.2600	-0.2120	-0.1820	-0.1320	-0.0990	-0.0590
S2T9	920.23	-0.2940	-0.2170	-0.1910	-0.1500	-0.1150	-0.0650
S2T10	911.51	-0.2820	-0.2260	-0.1910	-0.1410	-0.1040	-0.0620
Average	**904.00**	**-0.2775**	**-0.2213**	**-0.1910**	**-0.1435**	**-0.1083**	**-0.0628**

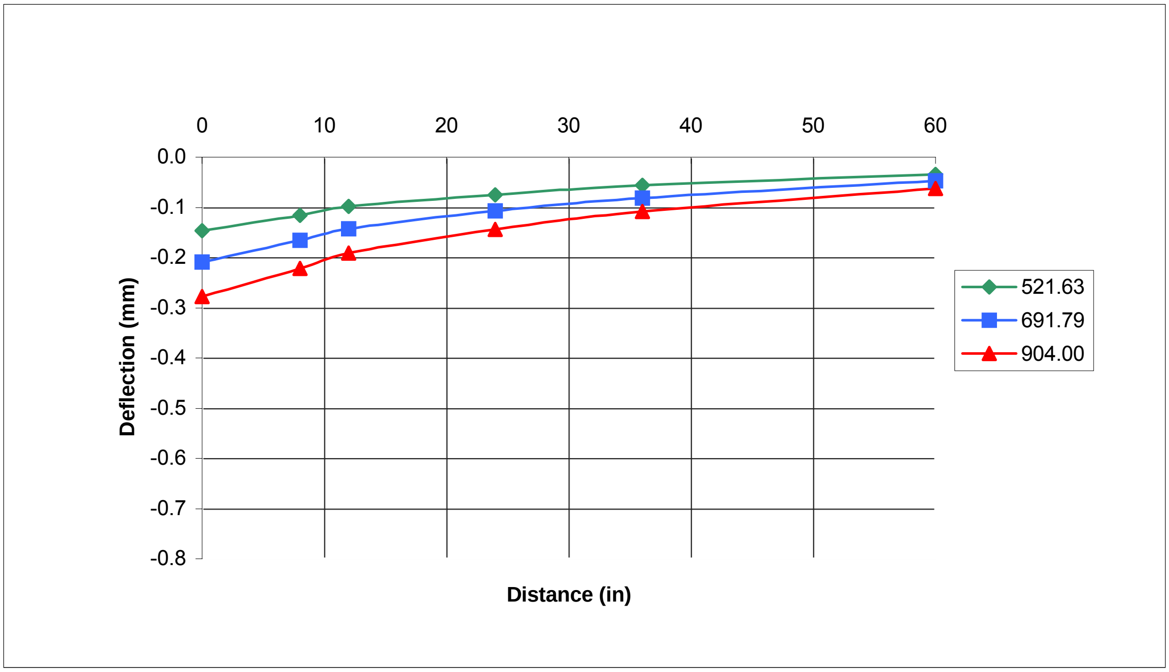


Figure 6.16 Average Deflections for a 10.5 in RCA Layer Section 2 (05/15/2001)

Table 6.14 Average Deflection for Lime Rock at Control Section, Four Readings.

Deflection L.R. 10.5 in Section 3 (05/15/2001)							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S3T1	549.64	-0.3450	-0.2210	-0.1470	-0.0660	-0.0430	-0.0290
S3T2	519.22	-0.3500	-0.2330	-0.1610	-0.0660	-0.0420	-0.0270
S3T7	547.26	-0.3770	-0.2550	-0.1730	-0.0770	-0.0520	-0.0350
S3T8	575.37	-0.3870	-0.2790	-0.1840	-0.0750	-0.0470	-0.0290
Average	**547.87**	**-0.3648**	**-0.2470**	**-0.1663**	**-0.0710**	**-0.0460**	**-0.0300**

Deflection L.R. 10.5 in Section 3							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S3T1	708.08	-0.4560	-0.3040	-0.2130	-0.1010	-0.0660	-0.0410
S3T2	704.24	-0.4670	-0.3230	-0.2340	-0.1040	-0.0630	-0.0390
S3T7	699.36	-0.4850	-0.3380	-0.2380	-0.1150	-0.0760	-0.0460
S3T8	741.00	-0.4840	-0.3640	-0.2510	-0.1140	-0.0710	-0.0410
Average	**713.17**	**-0.4730**	**-0.3323**	**-0.2340**	**-0.1085**	**-0.0690**	**-0.0418**

Deflection L.R. 10.5 in Section 3							
Sect#	**Load**	**Distance from the Applied Load (in)**					
Test#	**(KPa)**	**0**	**8**	**12**	**24**	**36**	**60**
S3T1	867.93	-0.5760	-0.3920	-0.2810	-0.1420	-0.0920	-0.0560
S3T2	863.11	-0.5770	-0.4090	-0.3030	-0.1430	-0.0850	-0.0500
S3T7	883.41	-0.5980	-0.4220	-0.3040	-0.1540	-0.1010	-0.0600
S3T8	869.88	-0.5990	-0.4540	-0.3210	-0.1520	-0.0940	-0.0530
Average	**871.08**	**-0.5875**	**-0.4193**	**-0.3023**	**-0.1478**	**-0.0930**	**-0.0548**

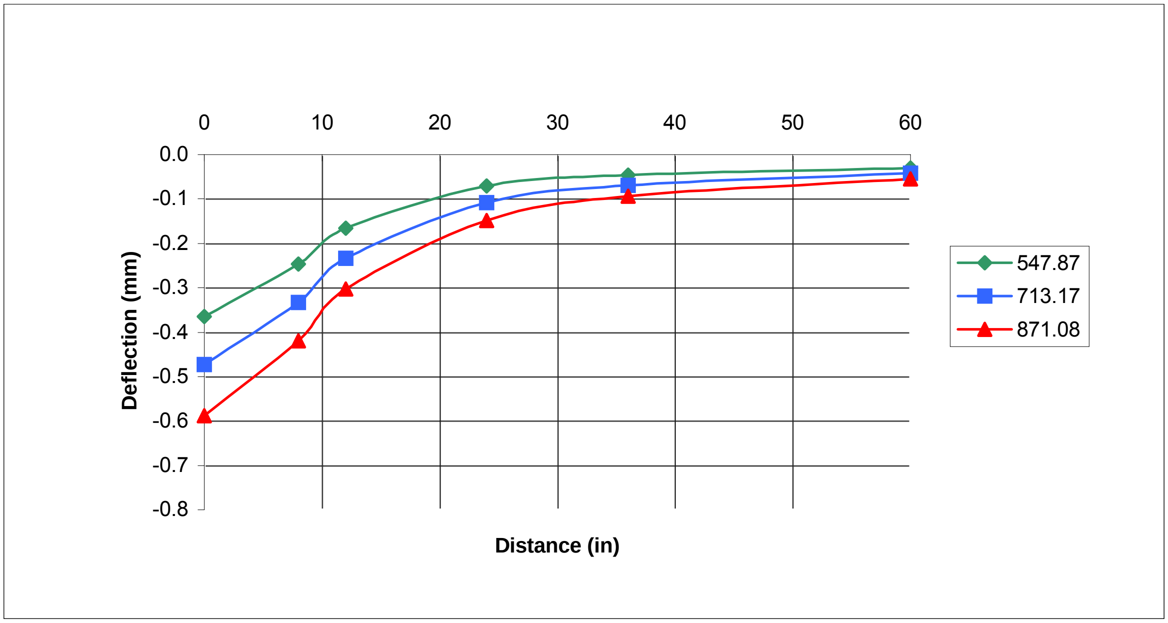


Figure 6.17 Average Deflections for a 10.5 in Limerock Layer Section 3 (05/15/2001)

Table 6.15 Comparison of First & Second FWD for a 8.0 in RCA Layer at different loads

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
First FWD	543.79	-0.2539	-0.1567	-0.1380	-0.1067	-0.0871	-0.0617	-0.0366
Second FWD	536.73	-0.1355	-0.1113	-0.0938		-0.0685	-0.0513	-0.0310
Firs FWD	734.36	-0.3446	-0.2144	-0.1801	-0.1468	-0.1201	-0.0846	-0.0495
Second FWD	710.28	-0.1895	-0.1578	-0.1318		-0.0988	-0.0685	-0.0393
Firs FWD	920.41	-0.4430	-0.2797	-0.2362	-0.1931	-0.1570	-0.1102	-0.0638
Second FWD	895.07	-0.2508	-0.2045	-0.1775		-0.1280	-0.0945	-0.0545

Table 6.16 Comparison of First & Second FWD for a 10.5 in RCA Layer at different loads

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
First FWD	543.79	-0.2505	-0.1656	-0.1400	-0.1147	-0.0940	-0.0672	-0.0394
Second FWD	521.63	-0.1460	-0.1165	-0.0983		-0.0748	-0.0565	-0.0340
Firs FWD	734.36	-0.3423	-0.2269	-0.1923	-0.1579	-0.1294	-0.0918	-0.0531
Second FWD	691.79	-0.2093	-0.1658	-0.1425		-0.1073	-0.0810	-0.0470
Firs FWD	920.41	-0.4404	-0.2946	-0.2507	-0.2063	-0.1689	-0.1195	-0.0683
Second FWD	904.00	-0.2775	-0.2213	-0.1910		-0.1435	-0.1083	-0.0628

Table 6.17 Comparison of First & Second FWD for a.10.5 in L.R Layer at different loads

Method	Load	Distance from the Applied Load (in)						
	(KPa)	0	8	12	18	24	36	60
First FWD	543.30	-0.3567	-0.2131	-0.1605	-0.1182	-0.0922	-0.0653	-0.0396
Second FWD	547.87	-0.3648	-0.2470	-0.1663		-0.0710	-0.0460	-0.0300
Firs FWD	730.94	-0.4814	-0.2882	-0.2187	-0.1614	-0.1257	-0.0889	-0.0536
Second FWD	713.17	-0.4730	-0.3323	-0.2340		-0.1085	-0.0690	-0.0418
Firs FWD	914.81	-0.6260	-0.3724	-0.2846	-0.2104	-0.1633	-0.1148	-0.0693
Second FWD	871.08	-0.5875	-0.4193	-0.3023		-0.1478	-0.0930	-0.0548

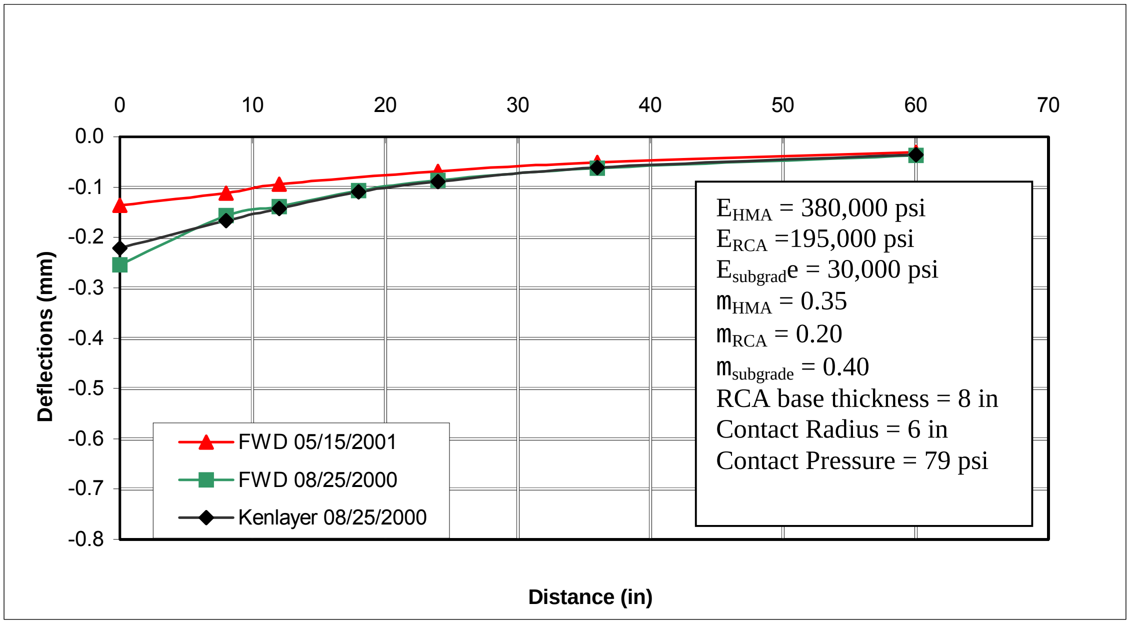


Figure 6.18 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 1)

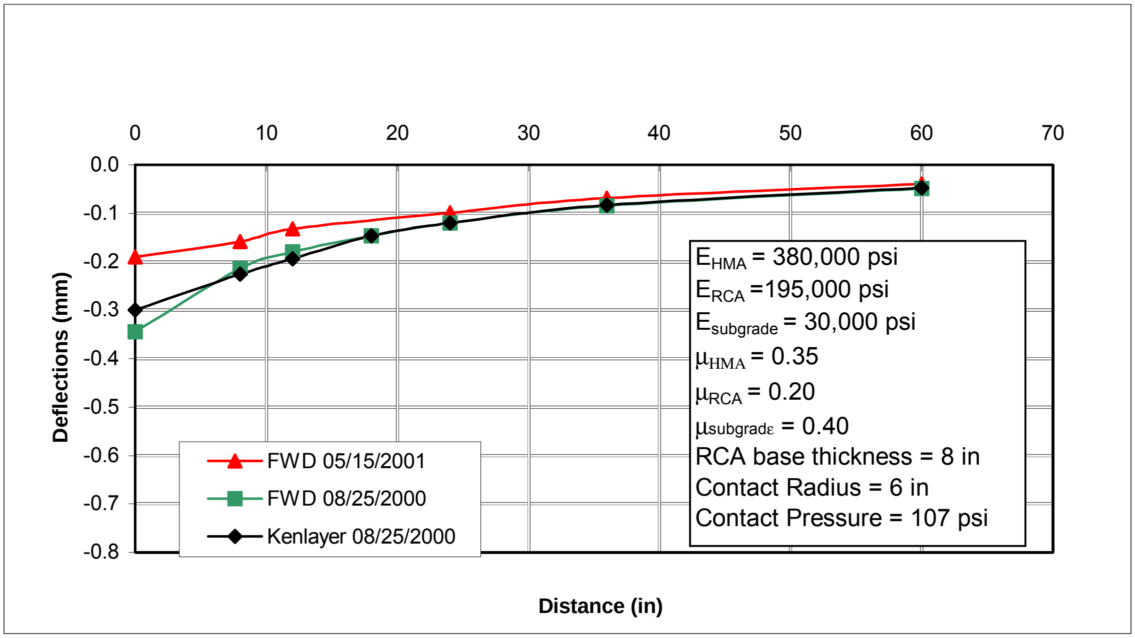


Figure 6.19 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 1)

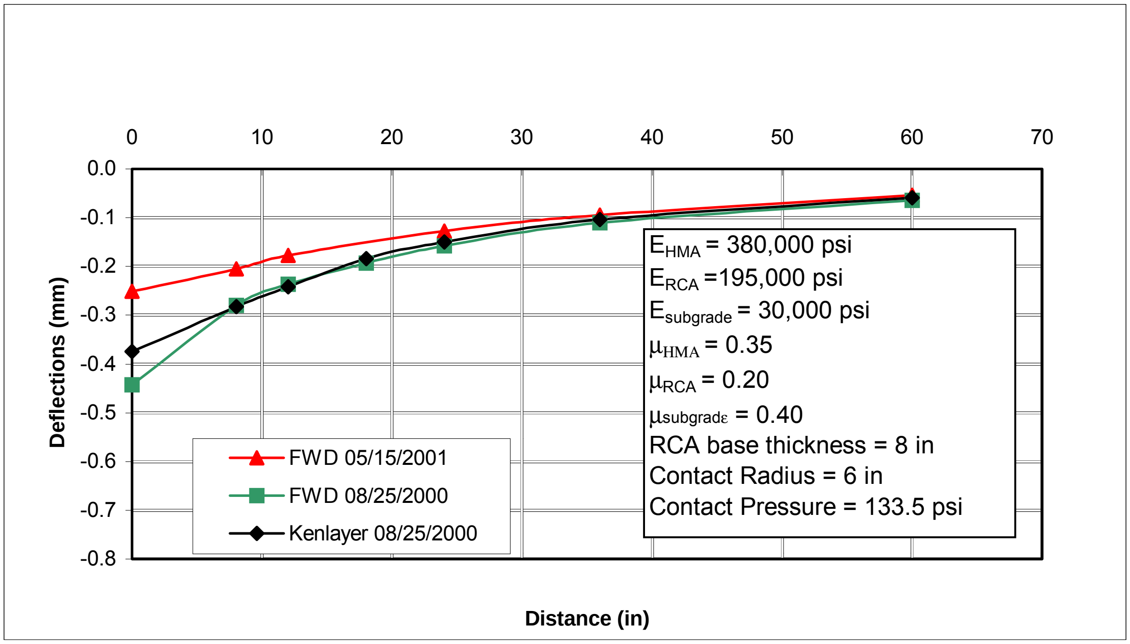


Figure 6.20 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 1)

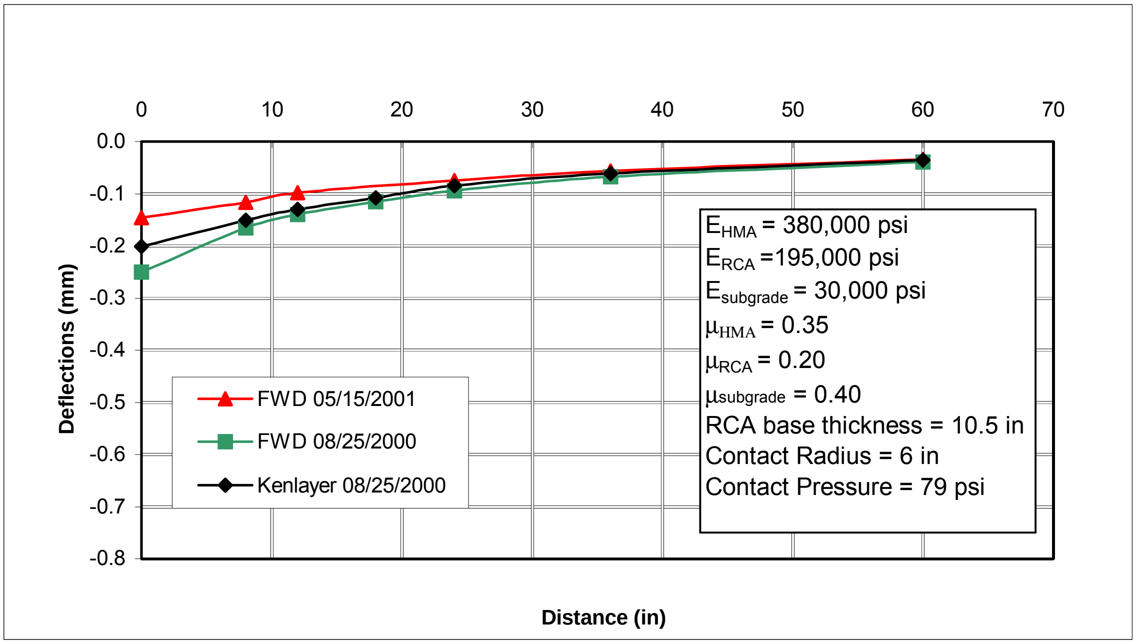


Figure 6.21 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 2)

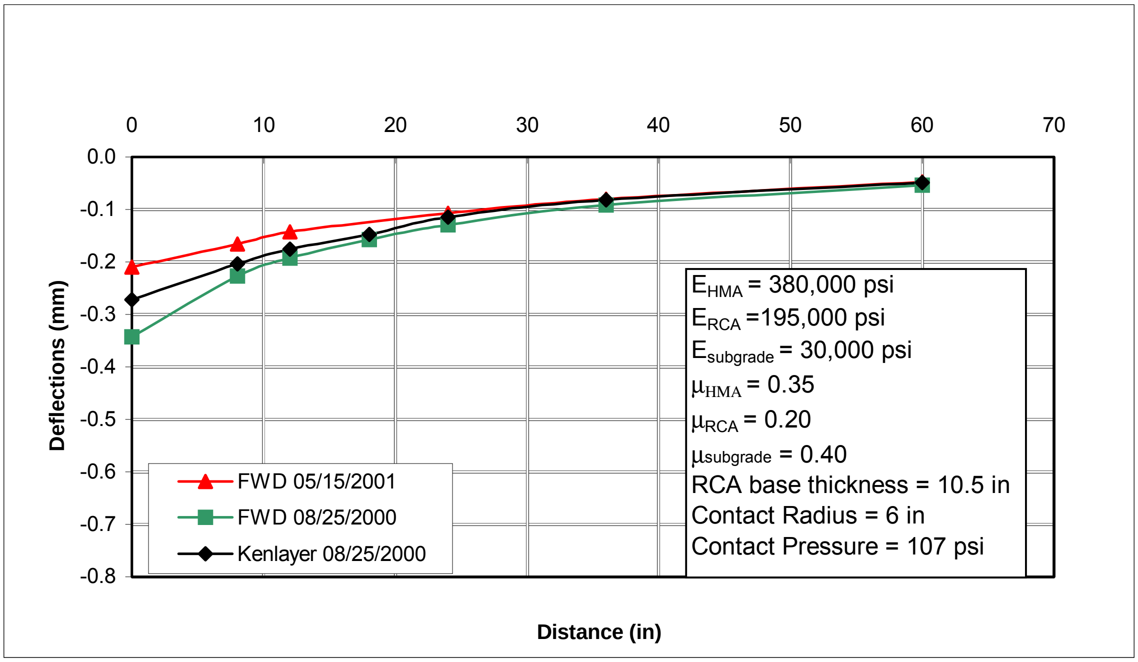


Figure 6.22 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 2)

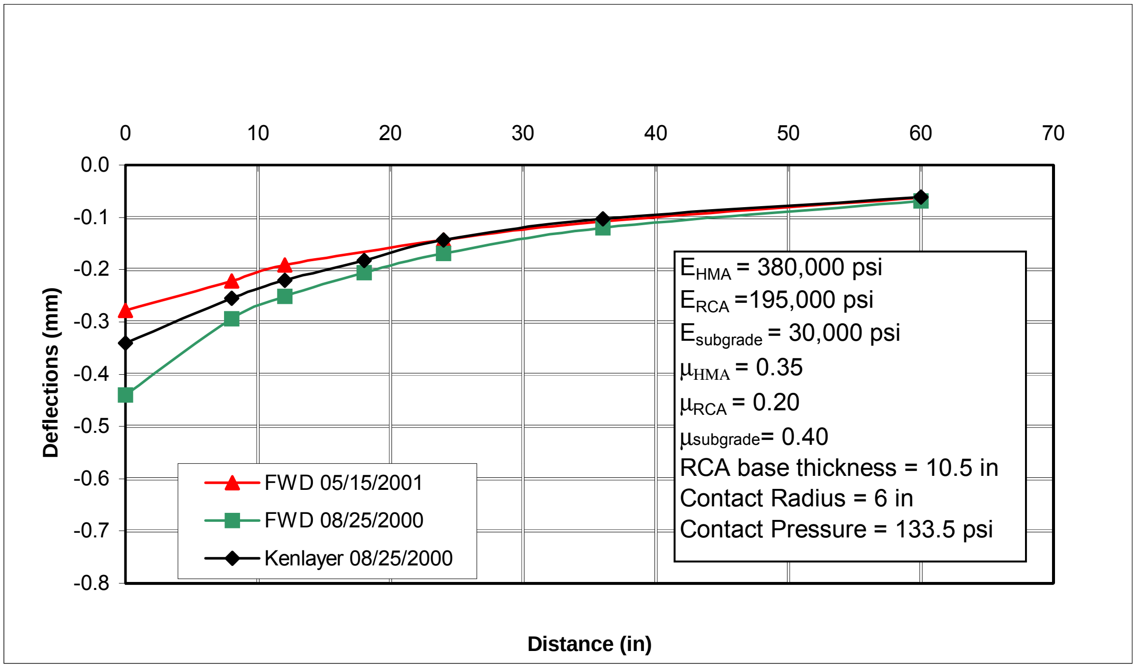


Figure 6.23 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 2)

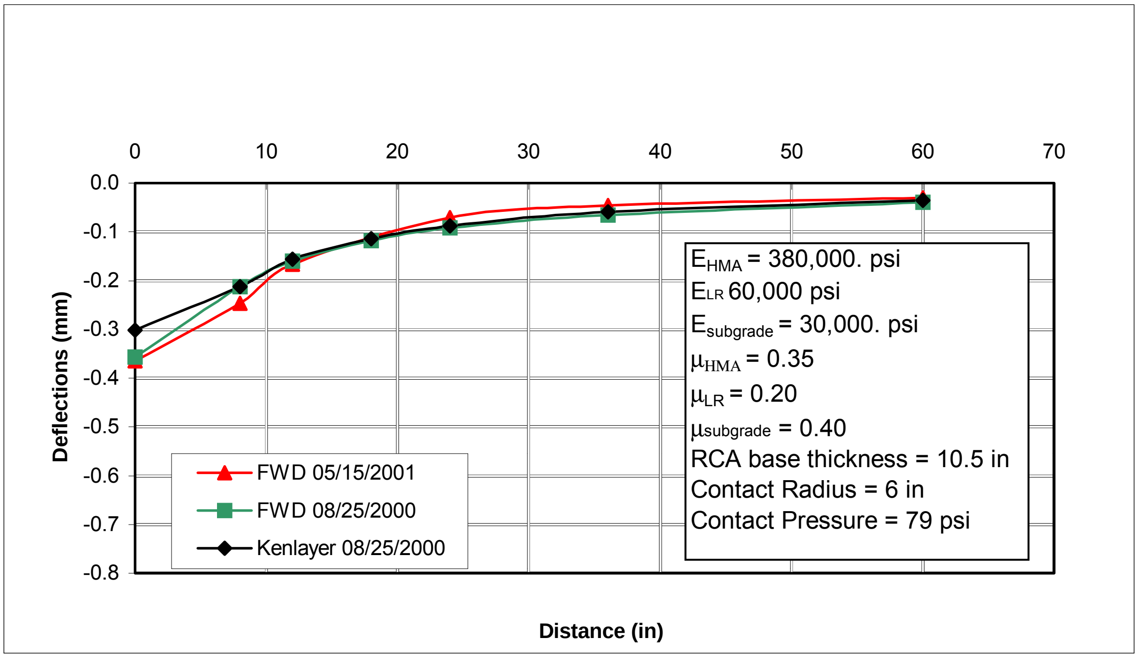


Figure 6.24 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 3)

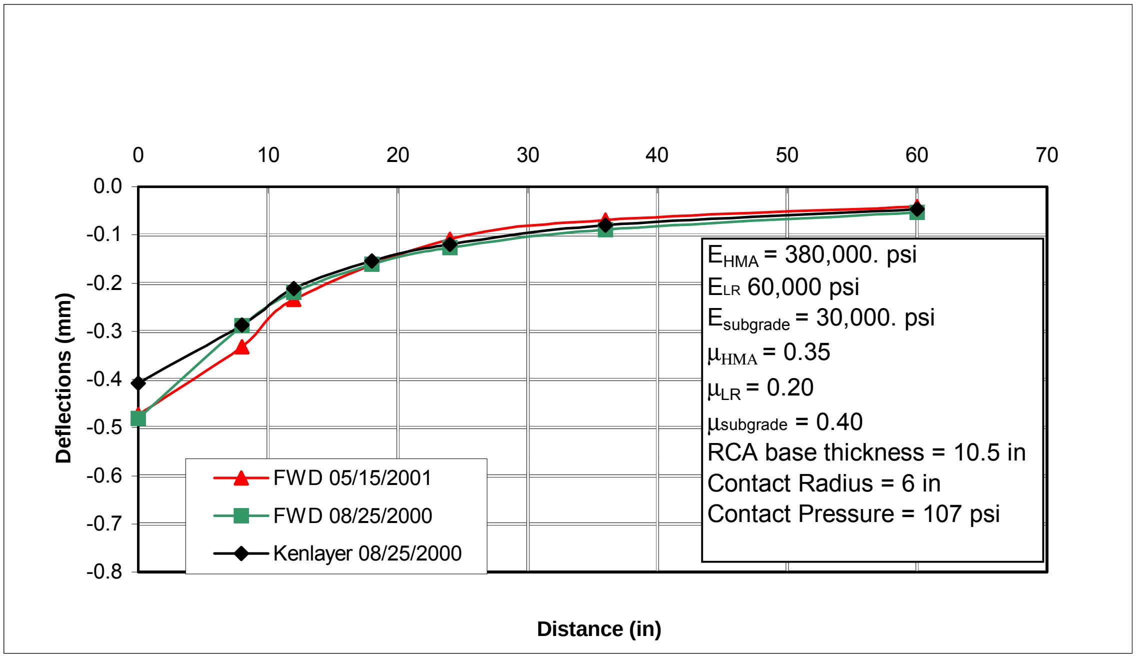


Figure 6.25 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 3)

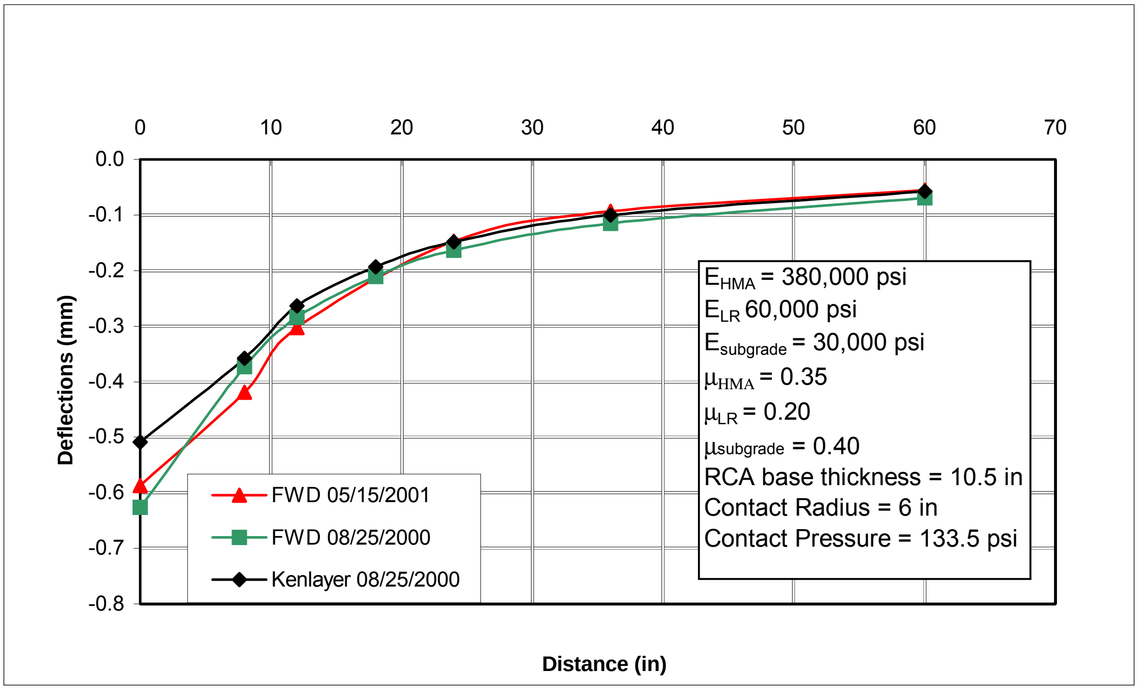


Figure 6.26 Comparison of Two FWD Tests and Kenlayer Deflection Basin (Section 3)

6.7 Rutting Measurement from Pavement Sections

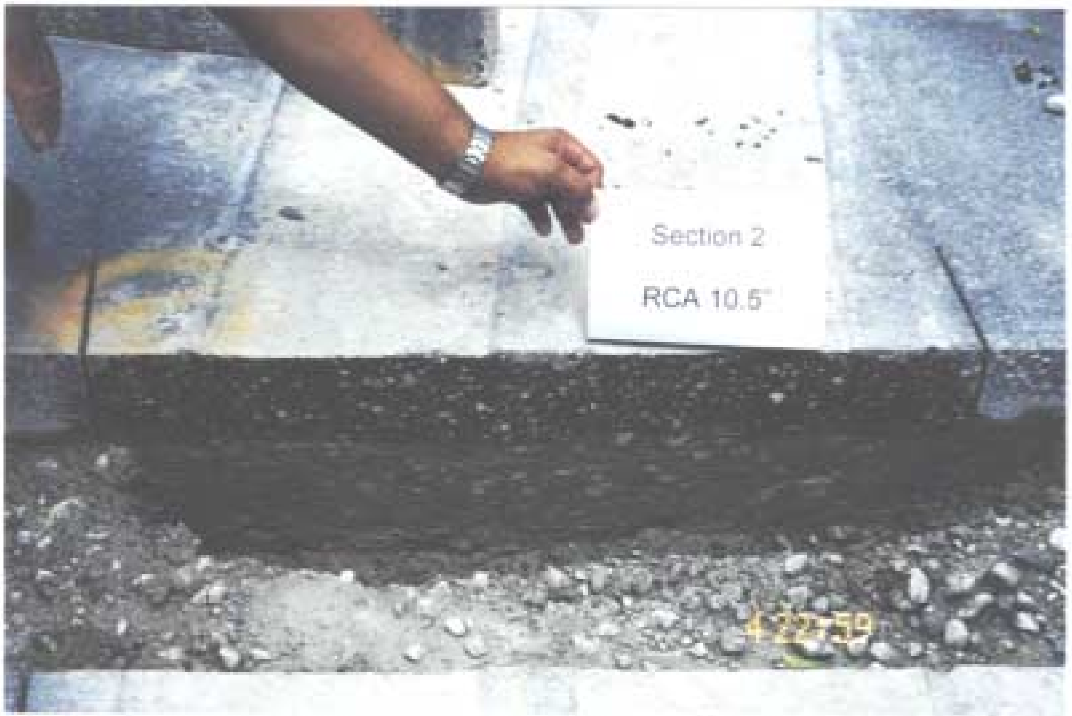
In order to determine if the base course has caused any rutting upon the completion of the performance test, a strip 12 in. (30 cm) wide and 10 in. (25 cm) deep was saw-cut from each test section and removed from the track. Photographs 6.2 and 6.3 show the saw-cut pavement sections, while Photographs 6.4 through 6.6 show the layer profiles of the test sections after the saw-cut. Photograph 6.7 shows a cut section of asphalt surface course with partial RCA base attached.

By carefully examining and measuring the cross-sectional profile and the cut sections, it is concluded that no significant rutting occurred on any base materials in this project. As seen in Photograph 6.7, the asphalt layer remains in practically straight line even after a total of 362,198 load repetitions. Since the rutting criteria based on the theoretical analysis for both RCA sections are: 1.8 x 10^6 and 6.9 x 10^6 of 22 kips (98 kN) load repetitions (see Table 6.10), no rutting is anticipated.

Photograph 6.2 Saw Cut Machine

Photograph 6.3 Saw Cut of Pavement Sections

Photograph 6.4 The Layer Profiles of Sections 1



Photograph 6.5 The Layer Profiles of Sections 2

Photograph 6.6 The Layer Profiles of Sections 3

Photograph 6.7 Cut Section of Asphalt Surface Course

6.8 Equivalent Structural Layer Coefficients of Pavement Components

The layer coefficient is a measure of the relative ability of a unit thickness of a given material to function as a structural component of the pavement system. In the AASHTO design method, the quality of the HMA, base, and subbase is indicated by their structural layer coefficients. Layer coefficients can be determined from tested road, or from correlations with material properties. In this study, the layer coefficient can be computed by either the resilient modulus or CBR. There are charts and equations developed for the correlations of resilient modulus versus layer coefficient and CBR versus layer coefficient. Equations (6.9) and (6.10) are the equations for the base layer coefficients established by the AASHTO (1986) correlation chart.

$$a_2 = 0.249 \log E_2 - 0.977 \tag{6.9}$$

$$a_2 = 0.0854 \log (CBR) - 0.0308 \tag{6.10}$$

a. Layer Coefficient Computed By Resilient Modulus, E_2:

The resilient moduli of test sections as determined from this study are: E_{HMA} = 380,000 psi, E_{RCA} = 195,000 psi, E_{LR} = 60,000 psi. The corresponding layer coefficient for the asphalt concrete, a_1, RCA, a_{2RCA}, and limerock, a_{2LR}, are, respectively:

$$a_1 = 0.42 \qquad a_{2RCA} = 0.34 \qquad a_{2LR} = 0.213$$

b. Layer Coefficient Computed By CBR via LBR:

In practice, FDOT adopts CBR = 0.8 LBR. Limerock LBR value of 126 based on one single source of material is given by FDOT Test Pit report (Boatman, 1999). LBR values of RCA as given in Table 4.10 in this study are 258 for the Test Section and 197.6 for the average of all samples except district 6. Therefore, the corresponding layer coefficients for the limerock and RCA are calculated using Equation (6.10) as:

a_{2LR} = 0.14 (Limerock from FDOT Test Pit)

a_{2RCA} = 0.17 (RCA from Test Section)

a_{2RCA} = 0.16 (RCA from all samples except district 6)

The difference of a_{2RCA} computed by the resilient modulus and the LBR may be attributed to the following reasons:

1- According to the FDOT Test Pit report, the RCA material constructed at UCF test track was delivered from the stockpiles of I-4 roadway slabs and considered as one of the best quality.

2- RCA resilient modulus, E_2, determined by FWD test at the test section was under the ultimate compaction at the optimum moisture condition, thus, the higher value of E_2 is anticipated. On the other hand, the LBR test of RCA in the laboratory was after the soaked condition, the material strength might have been weaken during the soaking period. However, use of LBR value for the design of the base course may be conservative and realistic.

3- From the plot of Equations (6.9) and (6.10) as shown in Figure 6.27, it is interesting to note that the curve of a_2 versus E_2 shows the increase of E_2, a_2 also increases. While the curve of a_2 versus CBR shows that the increase of CBR, a_2 is an asymptote of 0.17 value.

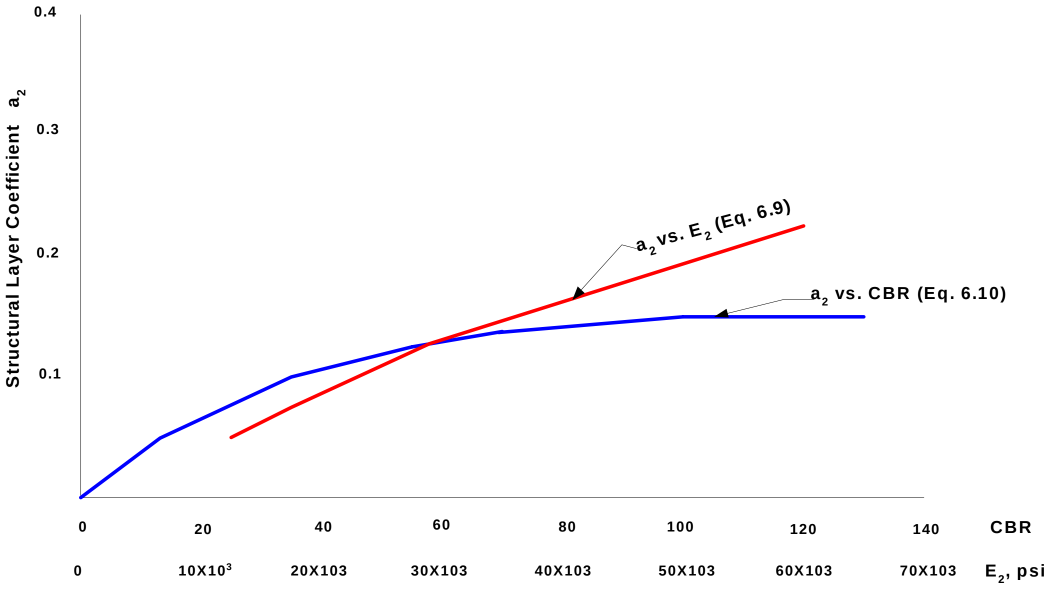


Figure 6.27 Plot of Equations (6.9) and (6.10)

6.9 Thickness Design and Thickness Equivalency of Base Course

The thickness design based on the structural layer coefficients and drainage conditions is given by Equation 6.9 as follows:

$$SN = a_1 D_1 + a_2D_2m_2 + a_3D_3m_3 \qquad (6.9)$$

Where: SN = Structural Number
a_1, a_2, a_3 = Layer coefficients for HMA, base and subbase respectively.
m_2, m_3 = Drainage coefficients for base and subbase

The pavement test section at the test track consists of only three layer components; asphalt concrete surface course, RCA base and limerock base course, and compacted subgrade. Assume m_2 = 1 for a good drainage base course, the structural number for RCA pavement and limerock pavement test sections can be computed as:

Section 1; $SN = 0.42 (4) + 0.34 (8) (1) = 4.4$

Section 2; $SN = 0.42 (4) + 0.34 (10.5) (1) = 5.25$

Section 3; $SN = 0.42 (4) + 0.213 (10.5) (1) = 3.92$

The structural number of each test section well exceeds 2.7 as required by FDOT specification because of a high layer coefficient due to the higher resilient modulus. If a conservative structural number of 3.0 is used for the design of base course thickness, the thickness of RCA base course required would be not more than 4.0 in. (10.2 cm), while the limerock base course thickness required would be less than 6.5 in. (16.5 cm). If the structure layer coefficients of RCA, a_{2RCA}, and limerock, a_{2LR}, are 0.16.and 0.14, respectively as determined by LBR, the thickness of RCA base and the Limerock base would be required a minimum of 8.0 in (20.4 cm) and 10.5 in. (26.7 cm), in order to meet the structural number of 3.0.

Based on the LBR values, the thickness equivalency of RCA to limerock can be estimated as:

$$H_{RCA} = (0.16 / 0.14) H_{LR} = 1.1 H_{LR}$$

This means that 1.0 in. (2.54 cm) of RCA will be equivalent to 1.1 in. (2.8 cm) of limerock. It must be clearly understood that the above-calculated figures are based solely on the sources of material collected and the results of this study.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7.1 Summary

The lack of landfill sites for waste disposal and the potential exhaustion of natural resources have led government and industry to consider the use of recycled wastes from old concrete structures as a new source for construction materials. In order to successfully use the recycled materials in pavement construction, it is necessary to develop a set of DOT guidelines and specifications.

To accomplish this objective, a literature review of previous work was completed. Then, a study was conducted to investigate the properties of the recycled concrete aggregates (RCA). Laboratory determinations of physical and mechanical properties of RCA include the gradation, particle shape, LBR, LA abrasion loss, absorption, surface soundness, sand equivalent, heavy metal, optimum moisture content and maximum dry density, hydraulic conductivity, and impurities.

In addition to the laboratory tests, a large-scale accelerated performance test was conducted through three pavement test sections: two for RCA and one for limerock at the University of Central Florida Circular Accelerated Test Track (UCF-CATT). The pavement test sections at the test track were experimentally and theoretically analyzed using a Falling Weight Deflectometer and the KENLAYER program. The program was utilized to back-calculate the resilient modulus and determine the strains at the bottom of surface course and the compressive strain at the top of the subgrade. The data obtained from the computer program were used to estimate the allowable load repetitions to failures in fatigue and rutting of the pavement system. A simulated life expectancy of the pavement test section was then calculated. Meanwhile, the performance of test sections was closely monitored and compared throughout the testing period. As a result of this study, pavement sections with RCA base demonstrated better performance than the limerock base control section as discussed in Chapter 5.

Guidelines and specifications for the use of RCA as base course for flexible pavement were developed based on the results of this study.

7.2 Conclusions

7.2.1 Literature review

A review of the existing literature about recycled concrete aggregates (RCA) revealed that the qualities of RCA are slightly lower than the qualities of virgin aggregates (VA) due to the cement attached to the stone aggregate. However, when this material is subjected to a more extensive refinement process, its properties will improve. The literature review also revealed that some European countries such as Germany, England, and Japan have already developed guidelines for the use of RCA and RCA concrete, and have also implemented strict regulations concerning the recycling process methodology applied to obtain RCA and the quality of the demolished concrete source.

Previous studies conducted on RCA have established that the water absorption of RCA increases with the diminution of the aggregate size. The mechanical properties analysis revealed that RCA particles are more angular than VA, have higher abrasion value, and their mechanical resistance decreases with the reduction of the maximum aggregate size. In addition, other tests on VA-concrete and RCA-concrete showed that RCA-concrete required about 10% more water than VA-concrete for a similar workability, and had about 25% less compressive strength and a 30% reduction in the modulus of elasticity.

7.2.2 RCA Producer Survey

A survey of recycled concrete plants in the State of Florida involving diverse aspects related to the RCA production method, its use, and cost was conducted. The survey revealed that 66.67% of the interviewees estimated that RCA could reduce construction costs because it is less expensive than virgin aggregates, and 73.33% agreed that RCA complied with City, County, and State specifications. There was no mention of other procedures that could be used to improve the material properties such as the bulk densities method and the washing process, which according to many studies could eliminate impurities and excess mortar adhered to the RCA particles. Table 3.6 summarized the survey from RCA producers.

7.2.3 Laboratory Testing

7.2.3.1 Gradation

Results of the gradation analysis indicated that the particle size distribution is one of the most important factors for the selection of RCA materials. The completed gradation test results were presented in Tables 4.2 to 4.7. The average gradation of most of the samples collected from the Districts met the requirements established in FDOT Section 204 with the exception of Districts 2 and 6. The gradation average for District 2 (Table 4.3) did not meet the FDOT Section 204 requirements due to anomalies present in the materials sampled in month of January. Samples from District 6 did not comply with the FDOT Section 204 specifications due to the poor conditions present for the material (large amounts of foreign materials) and the hazard associated with sample handling.

Figure 4.1 and Table 4.8 establish a statistical comparison between the gradation test results obtained from RCA samples and the FDOT Section 204 specifications for natural aggregates. This statistical comparison was based on the gradation average calculated from the averages listed in Tables 4.2 to 4.7. The information presented in Table 4.8, and Figure 4.1, (the standard deviation, and the confidence level) suggests that there were enough data to establish a 90 percent confidence interval for all the RCA material collected.

7.2.3.2 Limerock Bearing Ratio

The Limerock Bearing Ratio (LBR), indicative of the stability of a base course material was performed on the RCA samples. The results of the LBR were presented in Tables 4.9 and 4.10 as well as Figures 4.2 to 4.4. Table 4.10 shows that the arithmetic mean of LBR value including outliers (181.53) surpasses the 100 of VA required by FDOT. This fact denotes that a well-processed RCA is a proper material to be used as a base course in pavement construction. It concludes that the LBR for RCA may require a minimum of 100 psi.

7.2.3.3 Los Angeles Abrasion

The application of the Los Angeles (LA) Abrasion Test determined that RCA has a higher abrasion loss than natural aggregates because it is composed of natural stone coated with hydrated cement paste that is weaker and more prone to degradation than the natural stone to which it is attached. Test results presented in Table 4.11 and Figure 4.5 show that the range of LA abrasion losses for the RCA samples was 41.1% to 47.60%, less than the 45% specified by FDOT Section 204 for natural aggregates. The LA abrasion loss of the RCA material used for UCF-CATT fell slightly outside the total average of the 90% confidence interval. This may have been caused by irregularities presented by the RCA collected in some of the Districts.

7.2.3.4 Soundness

The soundness was tested by the sodium sulfate test approach. The RCA material sampled in December resulted in a soundness loss much greater than 15% after 5 cycles of sodium sulfate test. Table 4.13 shows the test results of RCA samples collected during the month of December from Districts 1,2,5, and 7. District 2 shows the highest loss at 70%. The average soundness loss is about 52%, well above the FDOT Section 204 specification of less than 15%.

Many countries and U.S. highway agencies have decided to waive the sodium sulfate test for recycled concrete aggregates since the sulfate test is inappropriate to apply to RCA because of the nature of the chemical attacks that take place on concrete materials. Thus, the sodium sulfate test should be waived.

7.2.3.5 Sand Equivalent

The Florida Department of Transportation requires that aggregates shall have a sand equivalent value of not less than 28%. The RCA samples tested in this project were found to have sand equivalent values much higher than 28%, as shown in Table 4.14. Thus, the sampled RCA materials meet the requirement of FDOT Section 204.

7.2.3.6 Hazardous Materials

The Environmental Protection Agency (EPA) has set the limit for lead emissions to 5 parts per million (ppm). As seen from Tables 4.16 and 4.17, the presence of lead in some RCA samples at Districts 2 and 4 is possibly related to the presence of lead-paint in the demolished concrete. The highest observed lead content of 12ppm from one sample at District 4 is clearly over the 5 ppm EPA limit. Since this is only one random sample, it may not represent the material characteristics of a full profile.

The Clean Air Act (CAA) requires the U. S. Environmental Protection Agency (EPA) to develop and enforce regulations to protect the general public from exposure to airborne contaminants that are known to be hazardous to human health, such as asbestos. An independent laboratory, Universal Engineering Sciences in Orlando, concluded that the laboratory test results indicated that no asbestos fibers were detected in any of the RCA samples.

7.2.3.7 Density

Tables 4.21 through 4.24 and Figures 4.7 through 4.12 show the results of maximum dry unit weights and optimum moisture contents determined by compaction tests conducted simultaneously at the UCF and FDOT District 5. The average maximum dry unit weight of 113.8 lb/ft^3 from the UCF laboratory and 114.8 lb/ft^3 from the FDOT-District 5 laboratory met the requirements of FDOT specifications for construction with the exception of the District 6 RCA sample. A standard of minimum dry unit weight of 110 lb/ft^3 and optimum moisture content of 11% may be expected for the qualifications of RCA.

7.2.3.8 Hydraulic Conductivity

The ideal permeability value of granular base (aggregates) for a good pavement performance should be 0.283 ft/day (10^{-4} cm/s) or greater. The results of permeability tests are presented in Tables 4.25 and 4.26 as well as Figures 4.13 and 4.14. In this study the tested material had a flow rate ranging from 0.09 to 1.4 feet per day (0.32 x 10^{-4} to 4.9 x 10^{-4} cm/s), which varies widely from the ideal parameter of 0.283 ft/day. The average RCA permeability in this project was found to be 0.67 ft/day (2.4 x 10^{-4} cm/s), which exceeds the recommended permeability.

7.2.3.9 Impurities

The average impurities content from all RCA samples is shown in Table 4.27. The impurity average was found to be 3.67% with District 6 samples included and 1.99% without District 6 samples. Both of these percentages are considered to be a negligible amount. These numbers can probably be lowered without incurring significant costs by employing further screening and processing methods of the material.

7.2.4 Deflection Measurements

The Falling Weight Deflectometer (FWD) tests were performed on the test sections at the beginning and the end of the performance test.

The results of the FWD deflection data along with deflection basin are presented in Tables 6.1 through 6.3 and Figures 6.2 through 6.4 for the first test. The second test results are shown in Tables 6.12 through 6.14 and Figures 6.15 through 6.17.

The comparisons between the first and the second FWD tests are presented in Tables 6.15 through 6.17. Figures 6.18 through 6.23 show the comparison of the two FWD tests along with the deflection basin computed by the KENLAYER program. As expected, the deflections taken at the second FWD test are lower than the first test since the pavement has been compressed by applying 362,198 load repetitions on the test track.

7.2.5 Theoretical Analysis

7.2.5.1 Back-Calculation of In-Situ Elastic Modulus Using KENLAYER

The KENLAYER program was employed to back-calculate the modulus of elasticity of the RCA base material by using the load-deflection data obtained from the FWD test. Using the resilient modulus of asphalt concrete of 380,000psi (55,112 kPa) determined from the laboratory cyclic load testing conducted by University of Florida, the moduli of the base and subgrade layers as bonded pavement components for the best fit of deflection basins were found to be E_{RCA}=195,000psi (28,281 kPa), E_{LR}=60,000 psi (8,702 kPa), and E_{Subg}=30,000 psi (4,350 kPa). The resilient modulus of RCA obtained from this analysis is comparable to the results of the Test Pit conducted by FDOT Materials Office in Gainesville.

7.2.5.2 Life Expectancy Analysis

The evaluation of the allowable number of repetitions for fatigue (N_f) and rutting (N_d) failures at RCA test sections was given in Tables 6.9 and 6.10. Since N_f and N_d are extremely high, both RCA sections 1 and 2 would probably not fail in fatigue and rutting.

The accelerated test facility was run for a total of 362,198 load repetitions (861,781 ESAL). By using the Equations 6.4 through 6.8 along with the data collected at the UCF-CATT and assuming take an average daily traffic (ADT) volume of 7,500 in one-direction for typical medium-heavy highway traffic with an average 6% of 18 kips (80 kN) truck, the life expectancy of RCA pavement system was calculated to be 36.9 years as given in Table 6.11.

7.2.6 Accelerated Performance Testing at UCF-CATT

Pavement distresses were monitored during the course of performance testing. The distresses were measured for rutting, cracking, and settlement at the end of the performance test.

7.2.6.1 Rutting

By carefully examining and measuring the cross-sectional profile and the cut sections, it is concluded that no rutting occurred in any of the test sections.

7.2.6.2 Cracking

A total of 16 transverse cracks and one longitudinal crack appeared along the wheel path in the limerock section. The longitudinal crack occurred at the end of the test section and was measured to be approximately 35 in. (90cm) long and the transverse cracks varied in length from 10 in. (25cm) to 31 in. (80cm). The largest transverse crack was measured to be approximately 1/8 in. (0.3cm) wide.

7.2.6.3 Settlement

There were two distinct settlements, both of which occurred at the end of test sections that connected the concrete slab to the two bridge decks. The settlement in the limerock section was 1¾ in. (4.5cm) deep compared to ¾ in. (2.0cm) in the RCA section.

7.2.7 Equivalent Structural Layer Coefficients

According to the resilient moduli of test sections determined from this study, the corresponding layer coefficients for the asphalt concrete, a_1, RCA, a_{2RCA}, and limerock, a_{2LR}, are computed, respectively:

$a_1 = 0.42$ $a_{2RCA} = 0.34$ $a_{2LR} = 0.213$

Based on the LBR values of limerock and RCA as determined by FDOT test pit and the results of this study, the layer coefficients for the limerock and RCA are computed as:

$a_{2LR} = 0.14$ (Limerock from FDOT Test Pit)

$a_{2RCA} = 0.17$ (RCA from Test Section)

$a_{2RCA} = 0.16$ (RCA from all samples except district 6)

7.2.8 Thickness Design and Thickness Equivalency of Base Course

If a conservative structural number of 3.0 and layer coefficients of 1.6 and 1.4 for RCA and limerock are used for the design of a base course, the thickness of RCA base and limerock base would be required a minimum of 8 in. (20.4 cm) and 10.5 in. (26.7 cm). Knowing the layer coefficients of RCA and limerock, the thickness equivalency of RCA to limerock can be estimated as:

$$H_{RCA} = (0.16 / 0.14)\ H_{LR} = 1.1\ H_{LR}$$

This means that 1.0 in. (2.54 cm) of RCA will be equivalent to 1.1 in. (2.8 cm) of limerock. It must be clearly understood that the above-calculated figures are based solely on the results of this study.

7.2.9 Summary of Test Results

The result of the sample tests is summarized in Table 7.1.

Table 7.1 Summaries of Test Results

Type of Test	Average Test Results
Gradation Test	**Average Gradation**
Sieve No.	
50 mm	100.0
37.5 mm	99.5
19 mm	83.2
9.5 mm	61.2
# 4	44.8
# 10	34.4
# 50	15.7
# 200	3.8
LBR Test	181.71
LA Abrasion Loss	44.02%
Sodium Sulfate test	52%
Sand Equivalent	70.5%
Heavy Metals	0 - 12 ppm
Asbestos	Free of Asbestos
Optimum Moisture Content	11.2% - 12.1%
Maximum Dry Unit Weight	113.8 lb/ft^3 – 114.8 lb/ft^3
Permeability	0.72 (ft/day)
Impurities	1.99% by weight
Structural Layer Coefficient (based on LBR value)	0.16

CHAPTER 8

GUIDELINES AND SPECIFICATIONS

The proposed guidelines and specifications for the use of RCA as a base course in flexible pavements based on the results of this study are presented in this Chapter.

8.1 Guidelines

RCA producers should provide some or all of the data suggested by the following tests:

- Gradation Test
- Limerock Bearing Ratio (LBR) Test
- LA Abrasion Loss Test
- Sodium Sulfate Test
- Sand Equivalent Test
- Heavy Metals Test
- Optimum Moisture Content and Maximum Dry Unit Weight Test
- Permeability Test
- Impurities Test
- Asbestos Test
- Material Characterization [Resilient Modulus Test (M_R)]

If there is any restriction or limitation for conducting any of the above-mentioned tests, the use of the recycled material should be based on agreements between the producer and the contracting agency.

8.1.1 Recommendations for The Selection and Processing of RCA

1. Before processing, the contractor must carefully select the demolished building or other structure and plan to have a separate storage area for the rubbles.
2. Reinforcing steel must be removed by using an overhead magnetic separator, then impact mills can be used to crush the rubble into various sizes, and finally air classifiers should be used to remove lightweight debris such as wood and plastic.
3. The RCA should be washed before using. Washing is also required to remove the dust as a measure of reducing potential tufa (porous limestone formed from calcium carbonate) formation. Additional quality control testing may be necessary to estimate the tufa precipitate (leachate) potential of RCA aggregates for embankment applications.
4. The material must possess comparable compressive and shear strengths of natural aggregate, meet gradation of particle size distribution, and provide proper workability.
5. RCA must not contain harmful impurities such as lead and asbestos, and it must not react with either cement or reinforcement when it is used for concrete add mixtures
6. The output quality must be guaranteed by systematic and rigorous monitoring, as well as intensive sampling and testing of the material

characteristics (including environmental properties). The basic requirement for producing high quality recycled aggregate is the selection of the material entering the preparation process; this presumes a well-organized acceptance and storage of the incoming material as well as effective material management.

8.1.2 Recommended Processing Methods

Since the properties of the recycled aggregate depend on the preparation process, special care has to be taken to guarantee its efficiency, so that it mainly influences the particle distribution and the particle shape.

The use of a combination of a jaw crusher in the first hackling phase and a rotating crusher in the second hackling phase is recommended for the best results regarding size distribution and shape. Similarly, the applications of dry and wet processes for classifying and elimination of harmful substances that RCA could contain is recommended. Furthermore, during the wet process the particles will be stripped of crushing dust, which is advantageous for concrete technology.

Another recommended technique involves the use of picking belts that enable the separation of large disturbing substances before raw material with particles size greater than 1.77 in. (45 mm) can be transformed into granulate by impact crushers.

Wet processing techniques become increasingly important when there is a high demand of concrete aggregates or raw materials for the production of masonry. Wet processing can be used in the production of concrete aggregates from mixed construction and demolition (C&D) waste, particularly concrete and masonry in order to achieve quality characteristics. This method provides a dust-proof surface that makes possible the separation of materials with a density lower than 124.8lb/ft^3 (2 g/cm^3). Currently the Jig Technique is the only method that can be applied to reach the separation of materials using the wet processing.

8.2 Specifications

The summary of the proposed specifications based on the results of this study is presented in Table 8.1.

Table 8.1 Proposed RCA Specifications

Type of Test	Proposed Specifications	FDOT Specifications
Gradation Test	**Gradation Limits (90% Confidence Interval)**	**Section 204**
Sieve No.	---	---
50 mm	Min. 100 - Max. 100	Min. 100 – Max. 100
37.5 mm	Min. 98 - Max. 100	Min. 95 – Max. 100
19 mm	Min. 65 – Max. 100	Min. 65 – Max. 90
9.5 mm	Min. 40 – Max. 83	Min. 45 – Max. 75
# 4	Min. 27 – Max. 63	Min. 35 – Max. 65
# 10	Min. 20 – Max. 49	Min. 25 – Max. 45
# 50	Min. 8 – Max. 24	Min. 5 – Max. 25
# 200	Min. 2 – Max. 6	Min. 0 – Max. 10
LBR Test	Min. 120	100
LA Abrasion Loss	**90% confidence Interval**	**Section 204**
	< 48%	< 45%
Sodium Sulfate test	N/A	15%
Sand Equivalent	N/A	≥ 28%
Heavy Metals	5 ppm	5 ppm
Asbestos	Free of Asbestos	Section 112 EPA
Optimum Moisture Content	**90% confidence Interval**	**See Section 200-6.4**
	10% - 12%	No Proper Values
Maximum Dry Unit Weight	**90% confidence Interval**	**Limerock**
	108 lb/ft^3 – 120 lb/ft^3	98% of Max. Dry Density
Permeability	0.10 to 1.40 (ft/day)	No Proper Values
Impurities	< 2.0% by weight	Substantially free of Impurities
Structural Layer Coefficient	0.16	0.15 (Standard Index 514)
Thickness Requirement	Min. 8.0 in. (20.3 cm)	10.5 in. (26.7 cm) Proposed for Limerock

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APPENDIX A

Compaction and Permeability Test Data Done UCF Lab

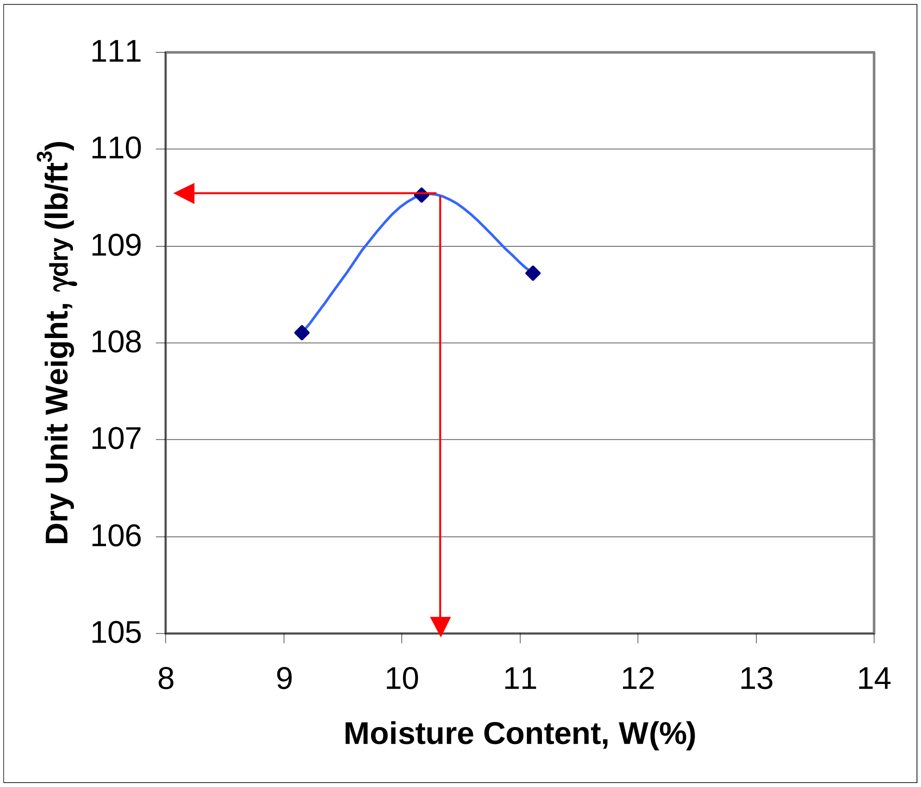


Figure A.1 Dry Unit Weight Vs Moisture Content, District 1 (December).

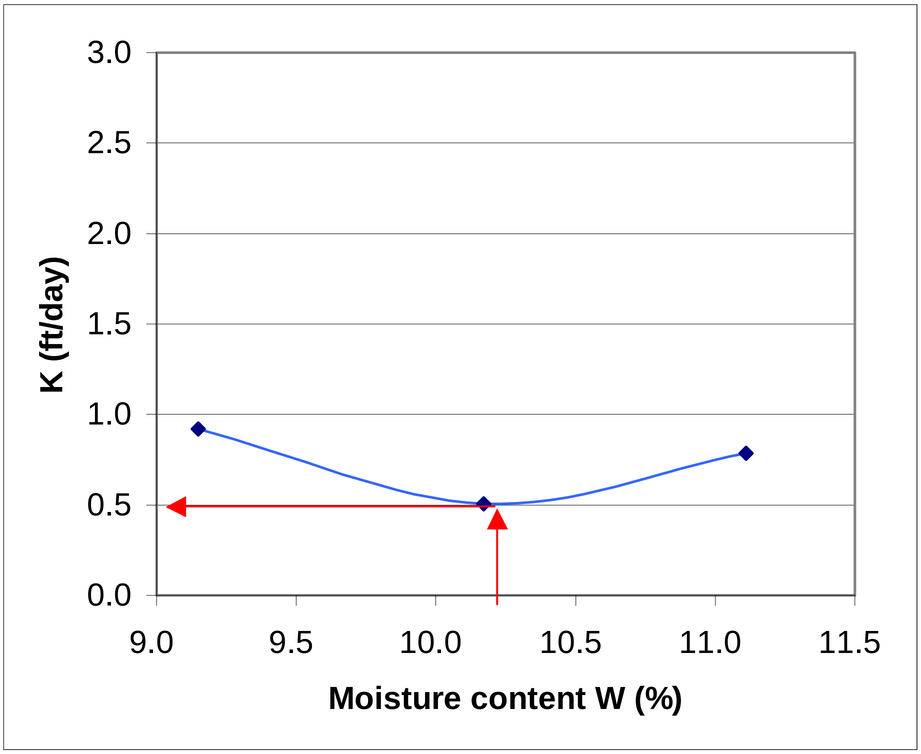


Figure A.2 Permeability Vs Moisture Content, District 1 (December).

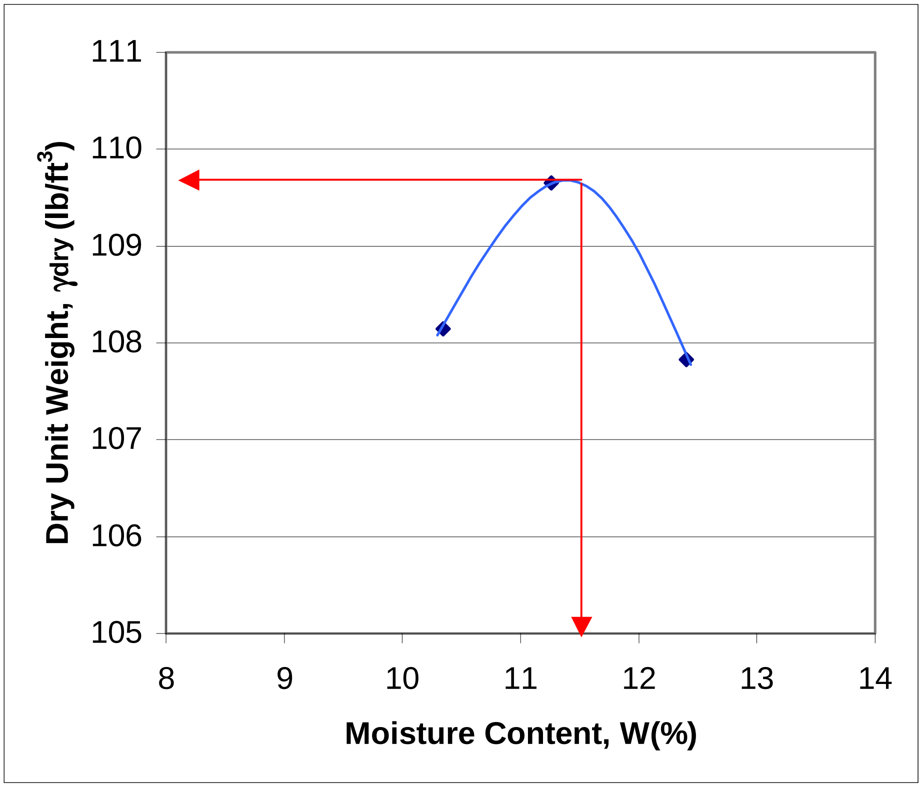


Figure A.3 Dry Unit Weight Vs Moisture Content, District 1 (January).

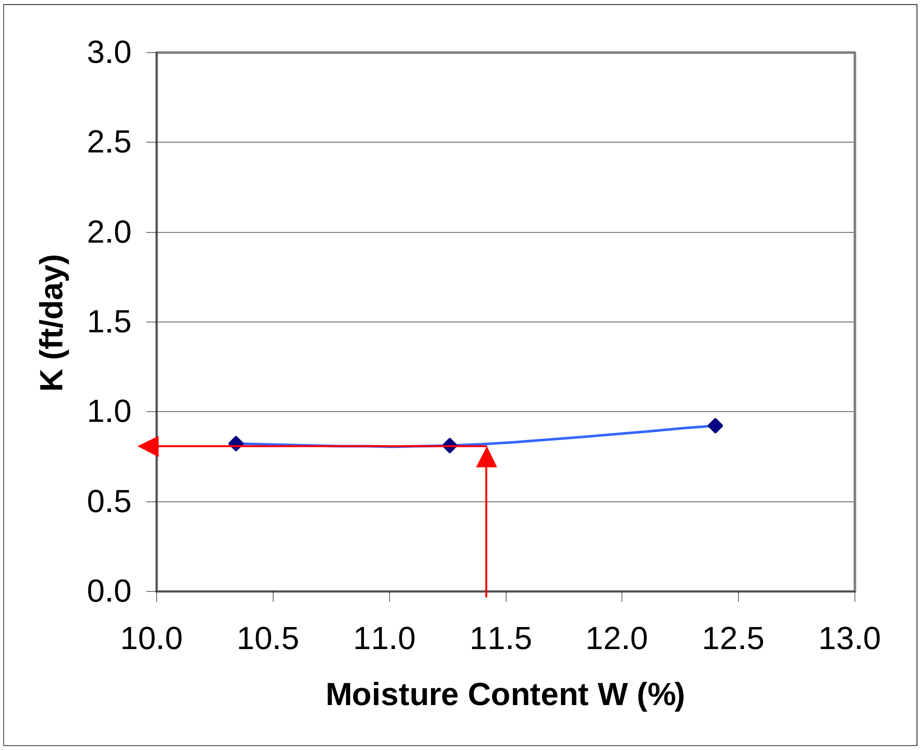


Figure A.4 Permeability Vs Moisture Content, District 1 (January).

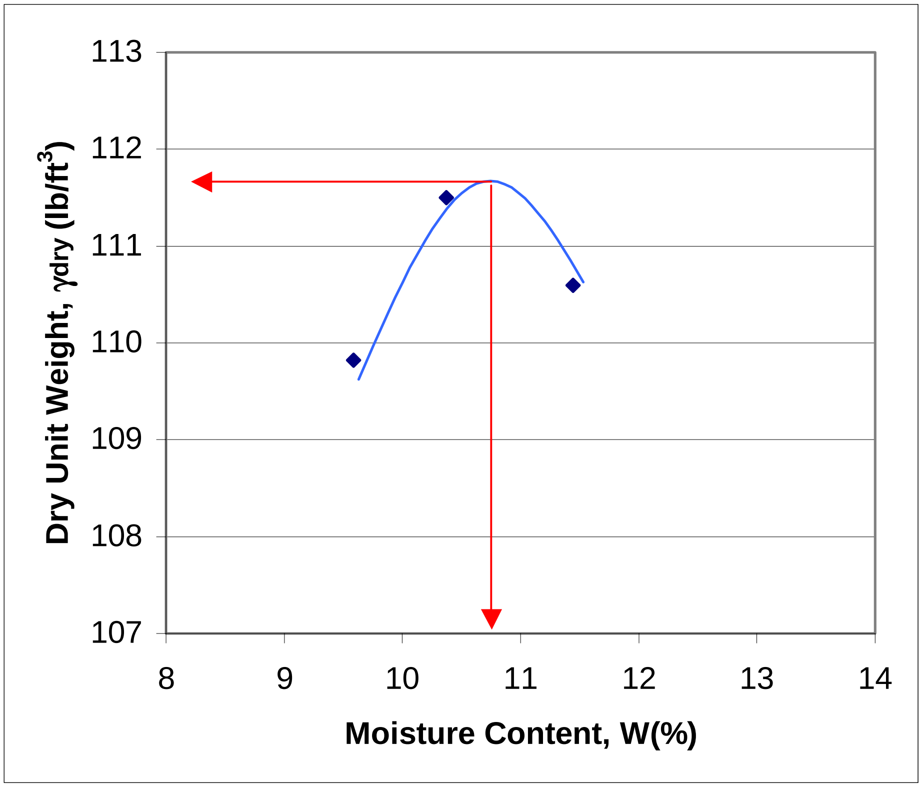


Figure A.5 Dry Unit Weight Vs Moisture Content, District 1 (February).

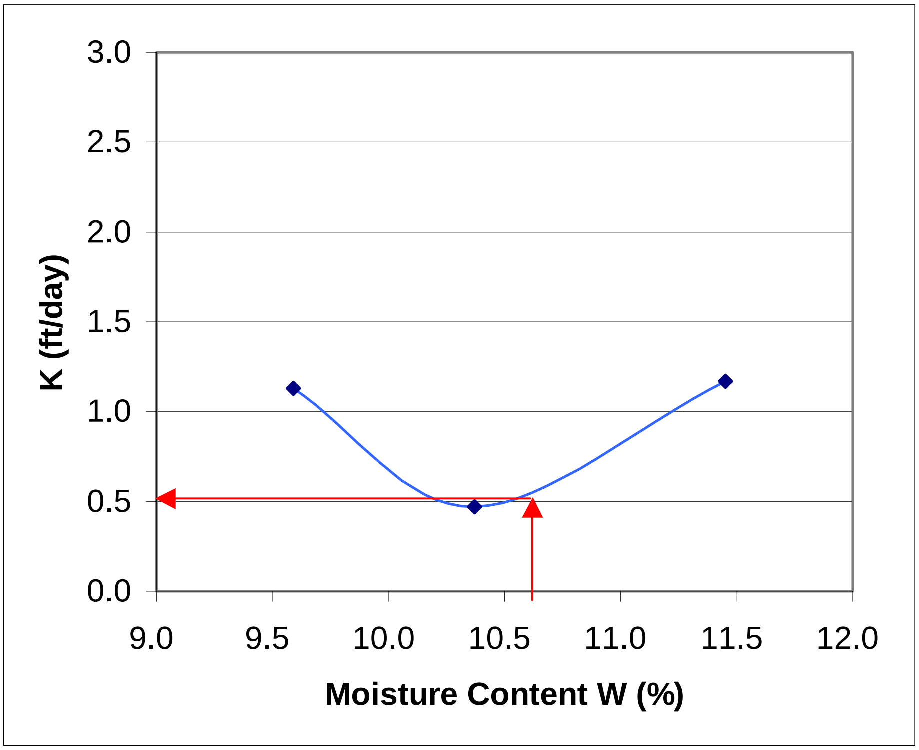


Figure A.6 Permeability Vs Moisture Content, District 1 (February).

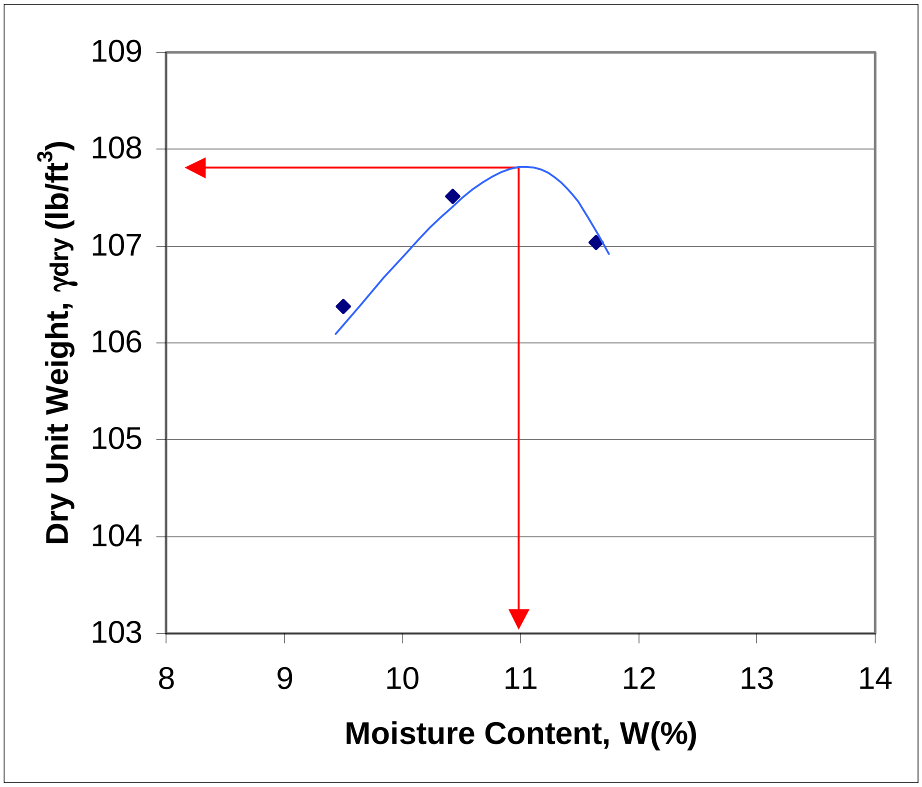


Figure A.7 Dry Unit Weight Vs Moisture Content, District 1 (March).

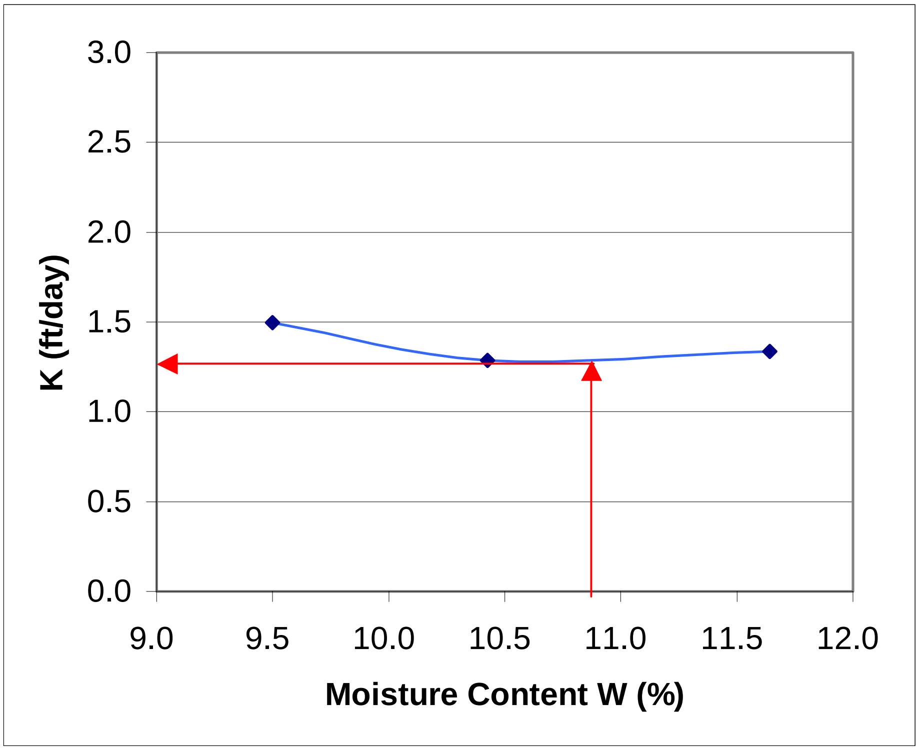


Figure A.8 Permeability Vs Moisture Content, District 1 (March).

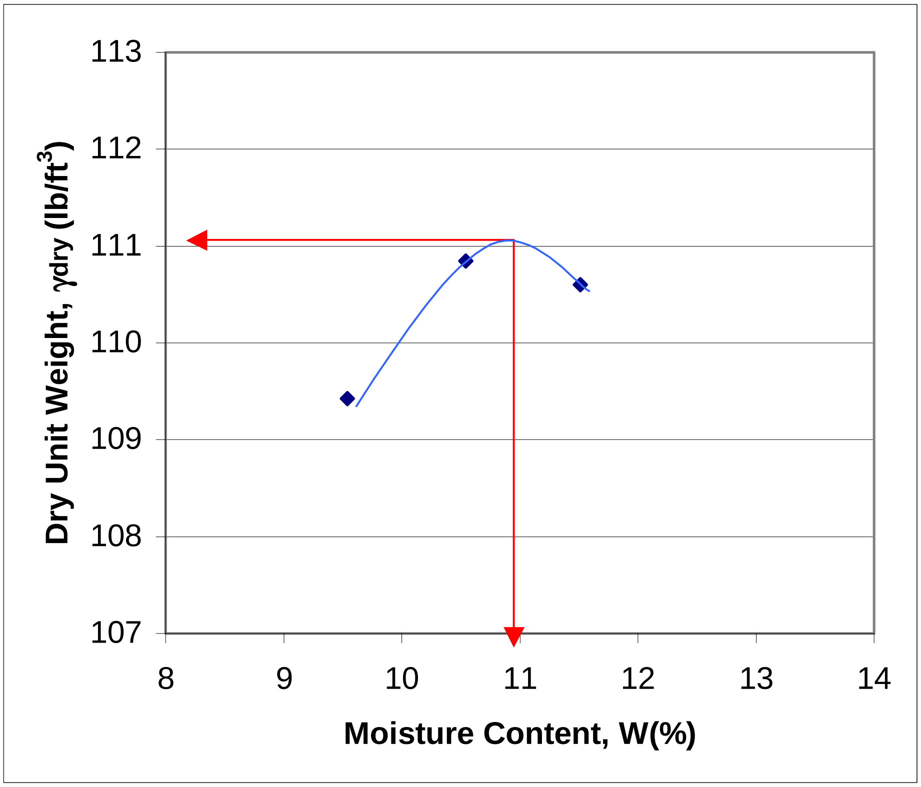


Figure A.9 Dry Unit Weight Vs Moisture Content, District 1 (April).

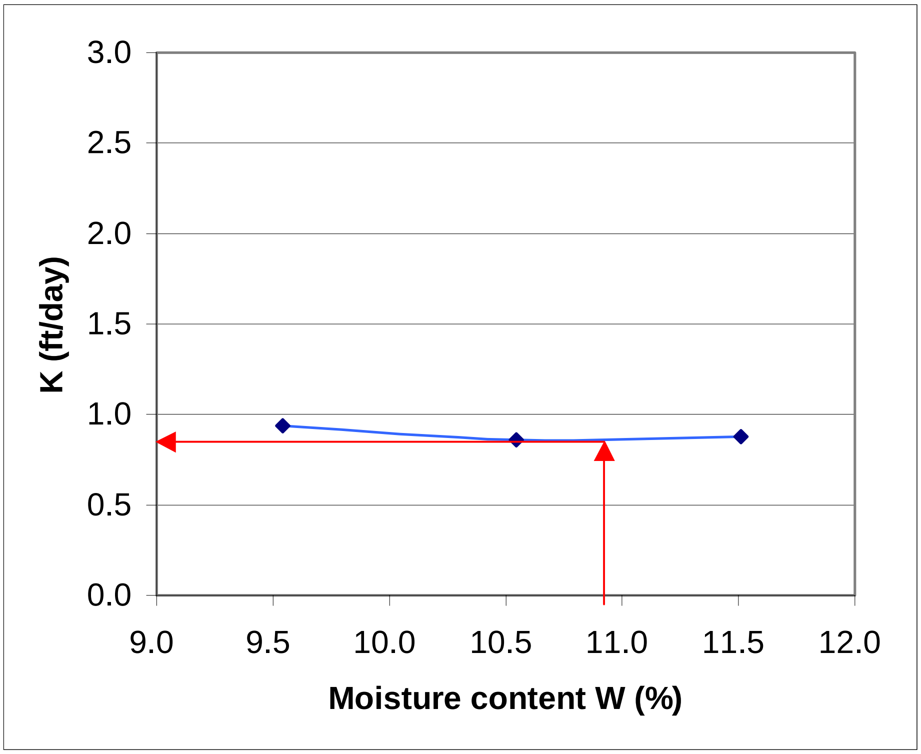


Figure A.10 Permeability Vs Moisture Content, District 1 (April).

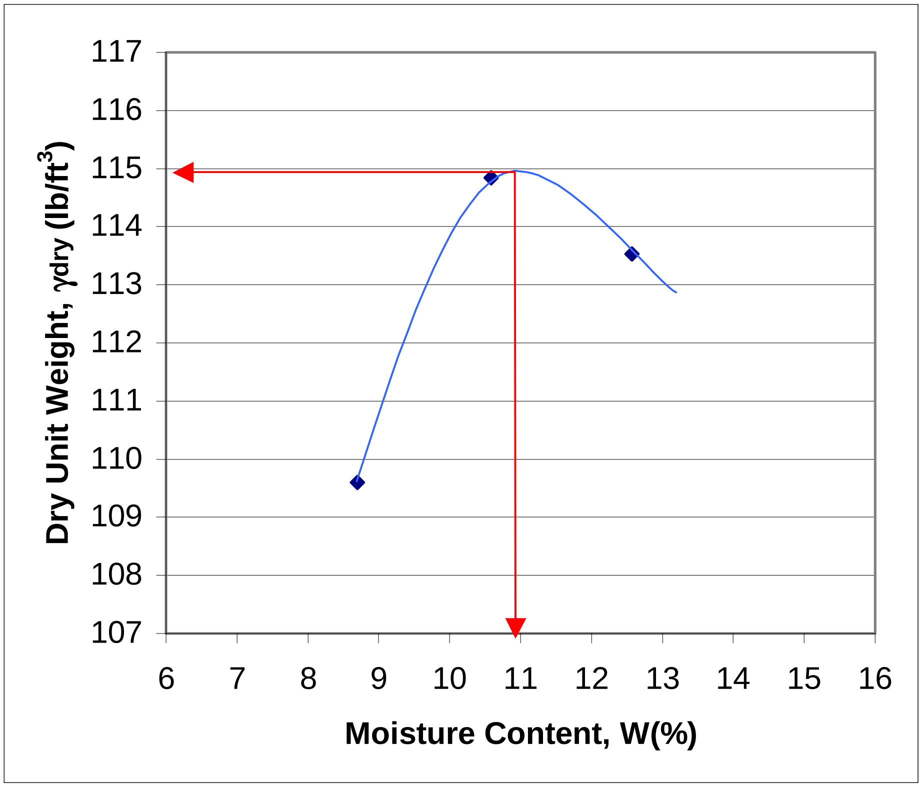


Figure A.11 Dry Unit Weight Vs Moisture Content, District 1 (May).

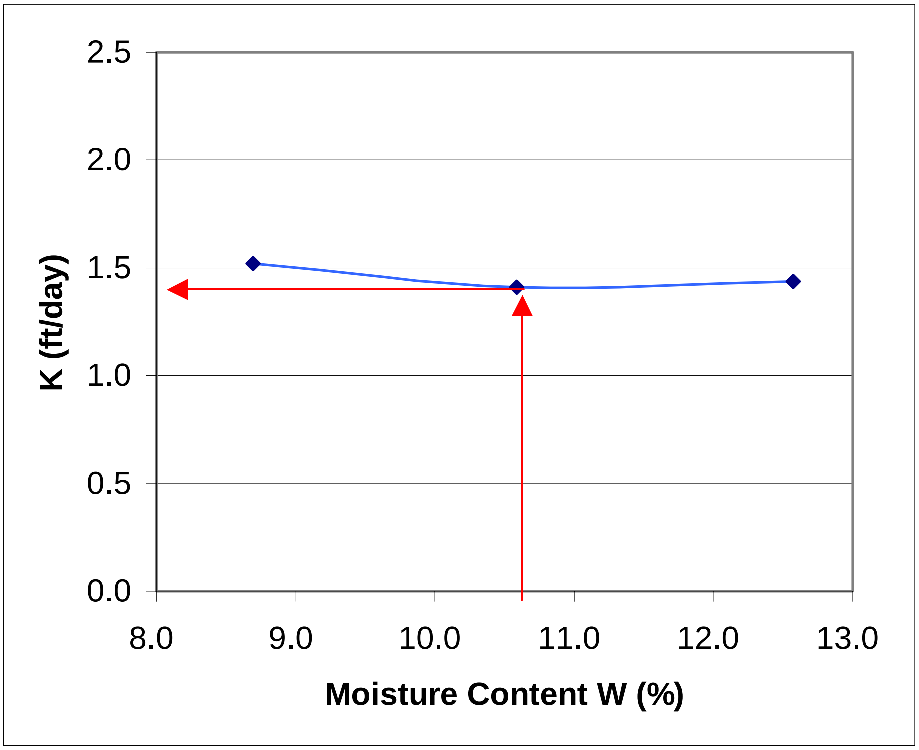


Figure A.12 Permeability Vs Moisture Content, District 1 (May).

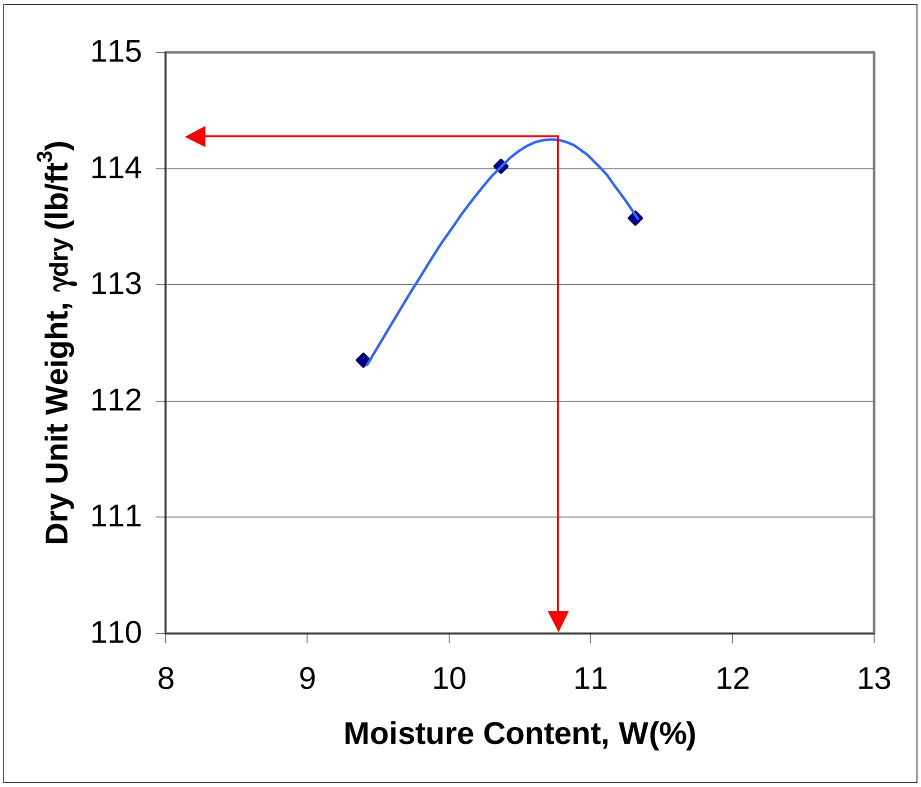


Figure A.13 Dry Unit Weight Vs Moisture Content, District 2 (December).

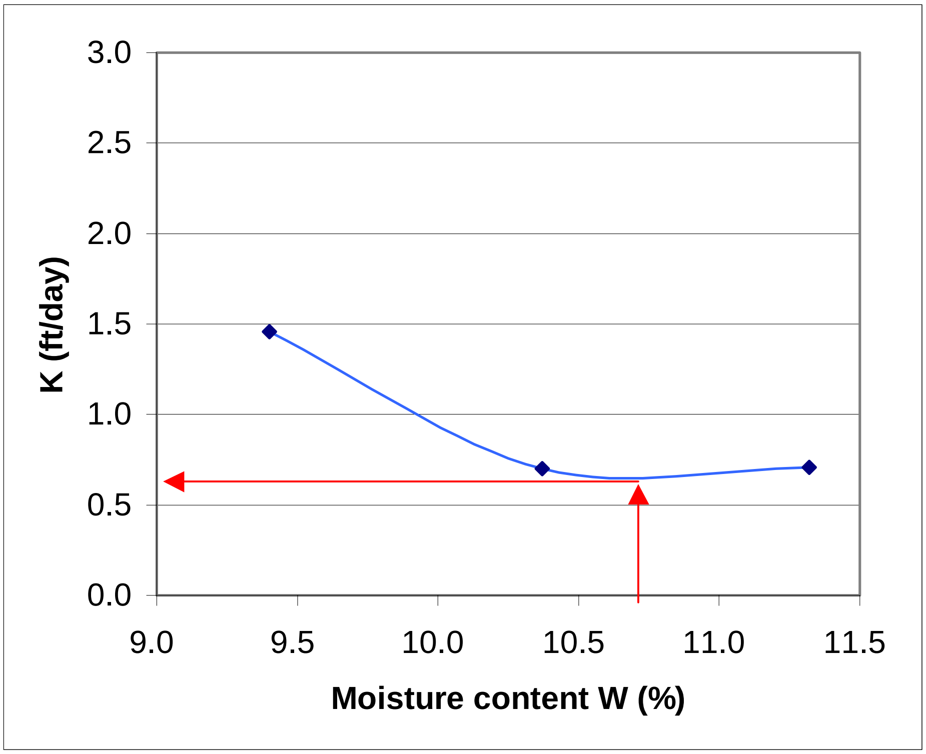


Figure A.14. Permeability Vs Moisture Content, District 2 (December).

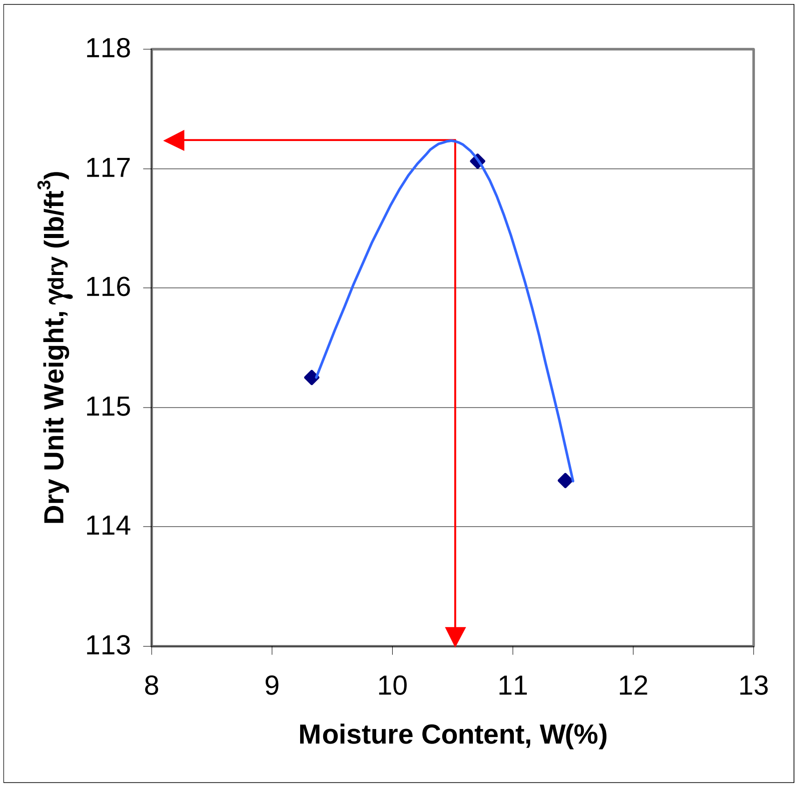


Figure A.15 Dry Unit Weight Vs Moisture Content, District 2 (Jan.).

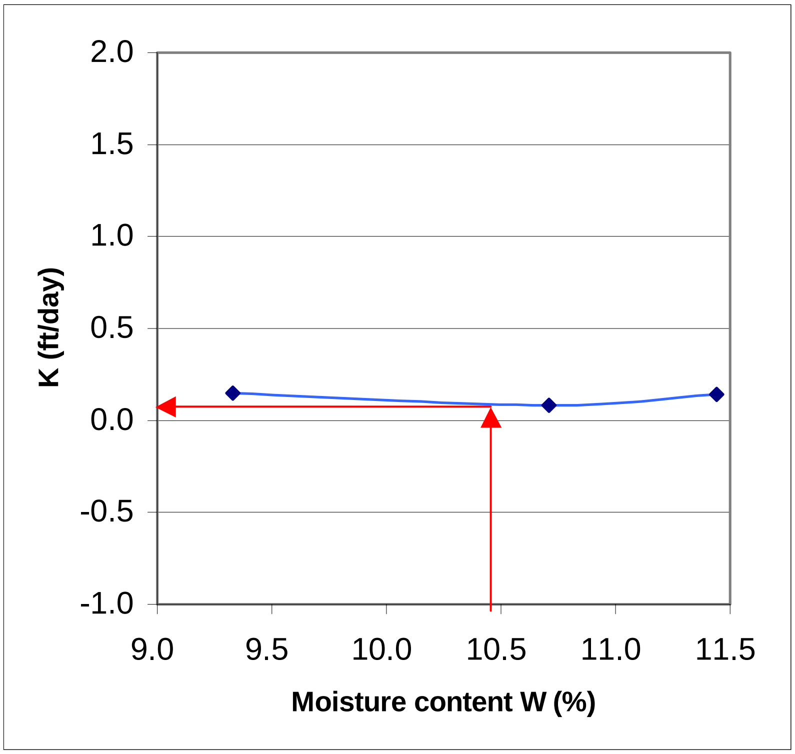


Figure A.16 Permeability Vs Moisture Content, District 2 (January).

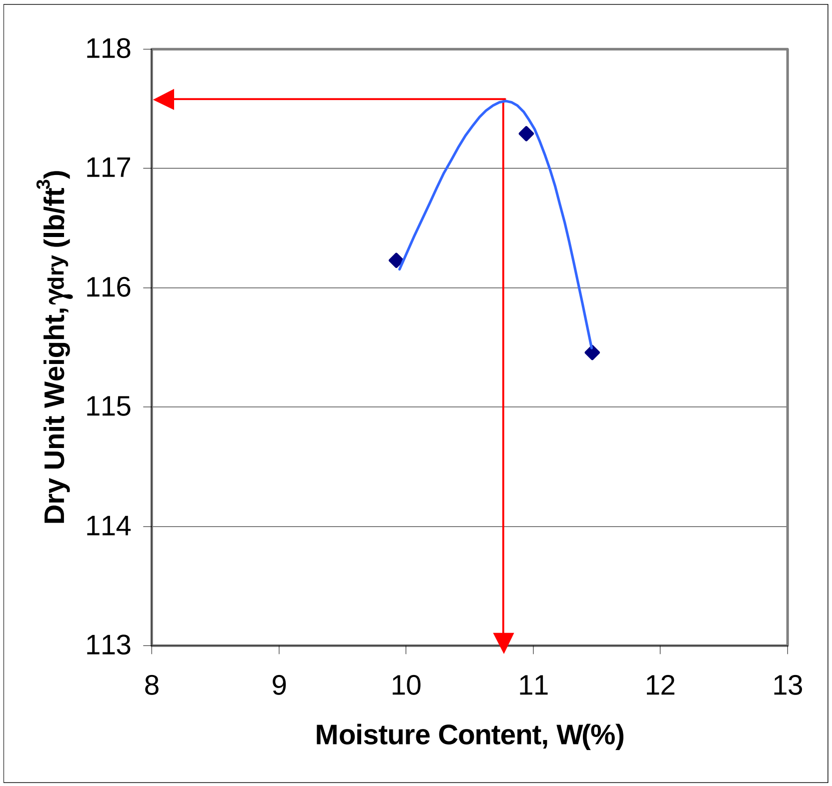


Figure A.17 Dry Unit Weight Vs Moisture Content, District 2 (Feb.).

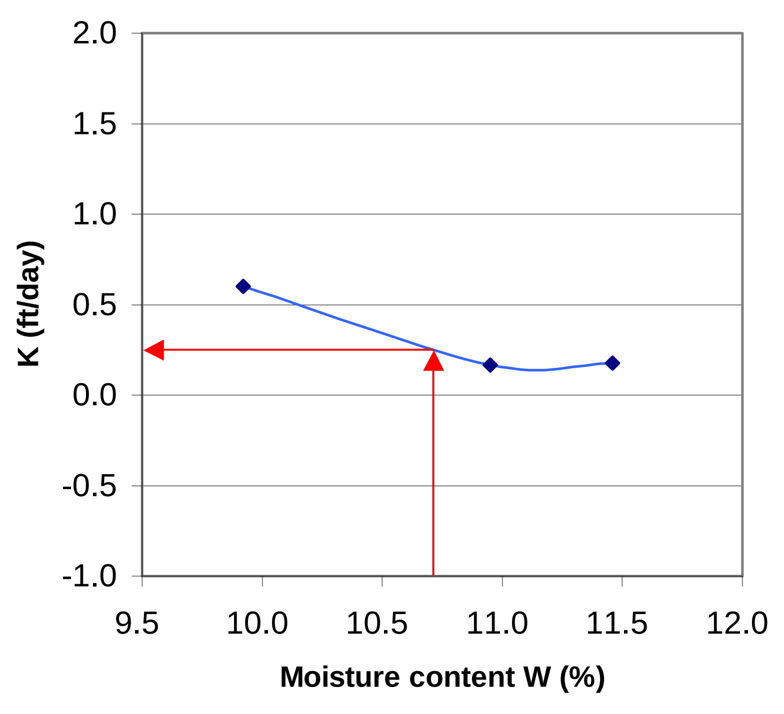


Figure A.18 Permeability Vs Moisture Content, District 2 (February).

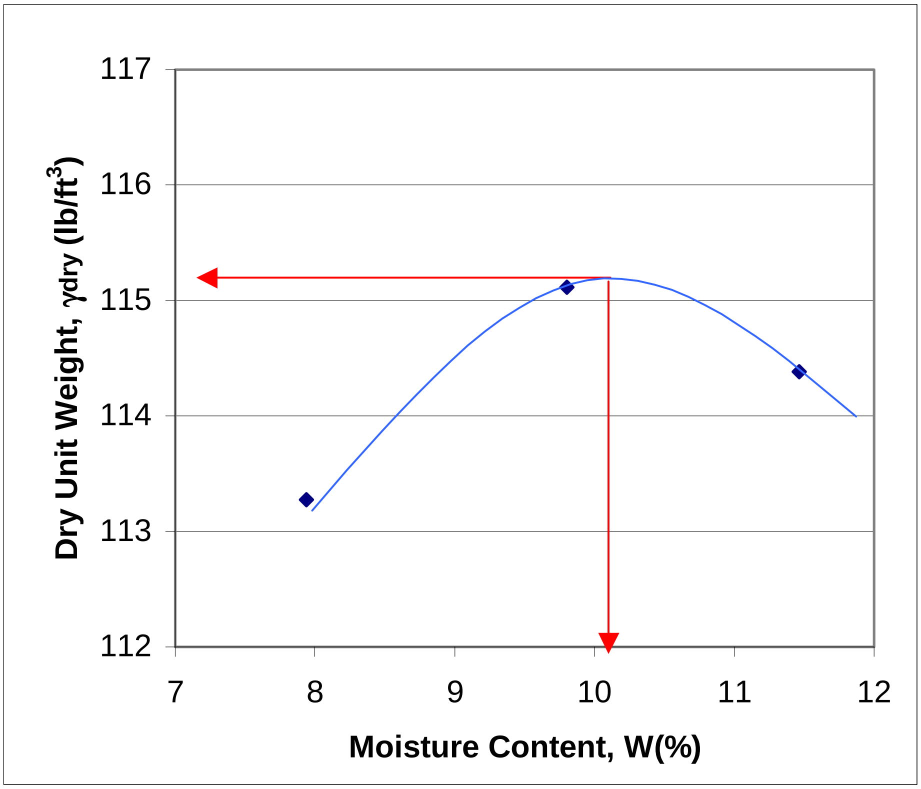


Figure A.19 Dry Unit Weight Vs Moisture Content, District 2 (March).

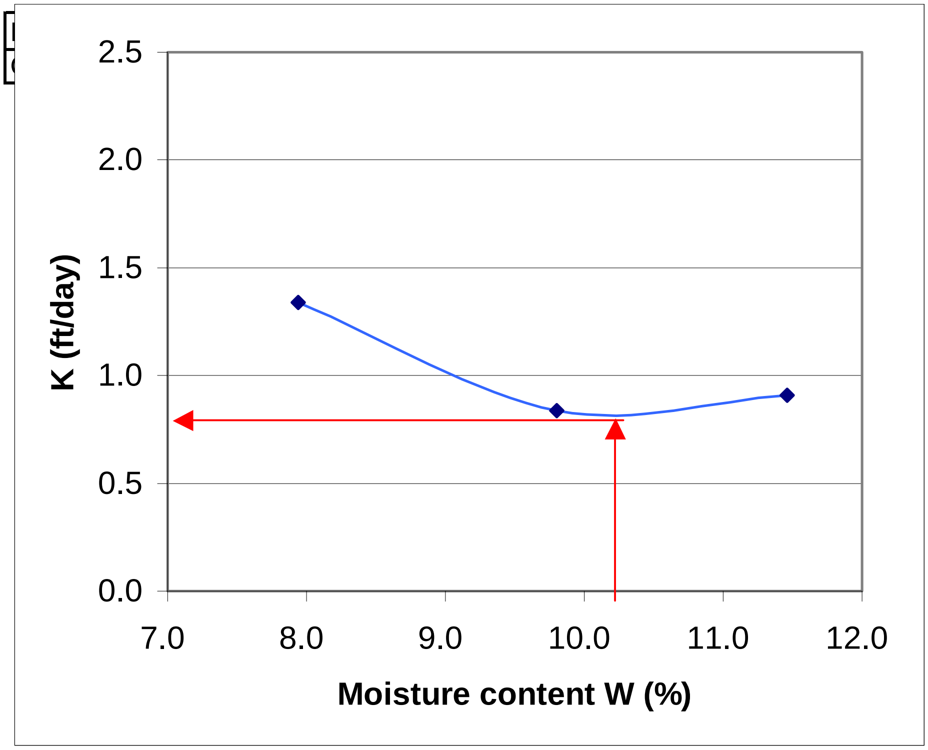


Figure A.20 Permeability Vs Moisture Content, District 2 (March).

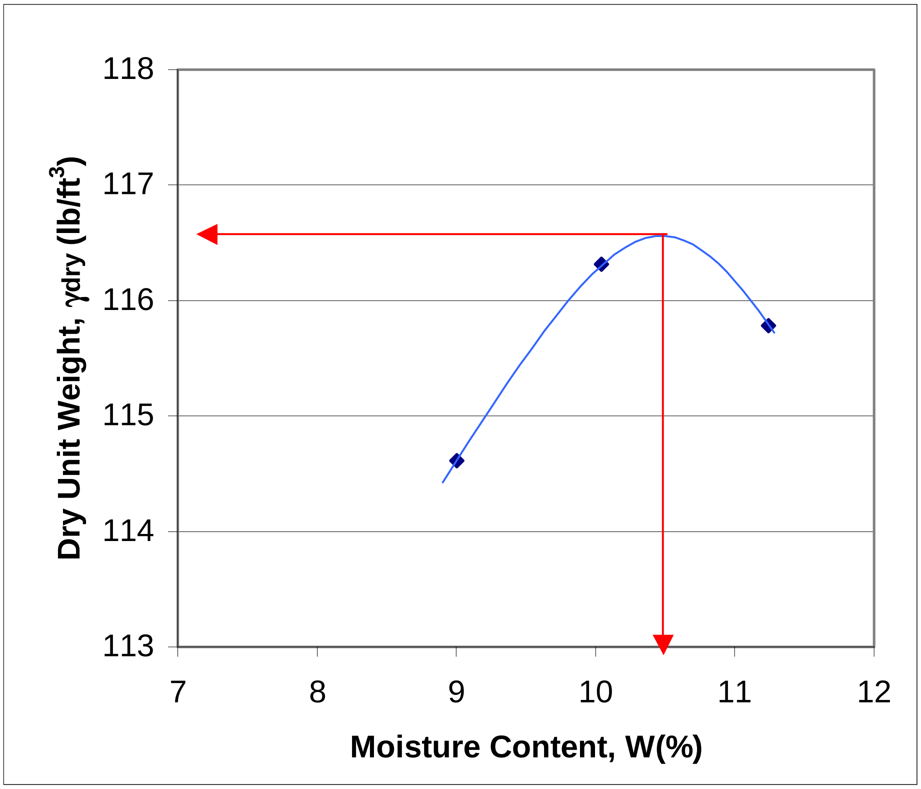


Figure A.21 Dry Unit Weight Vs Moisture Content, District 2 (April).

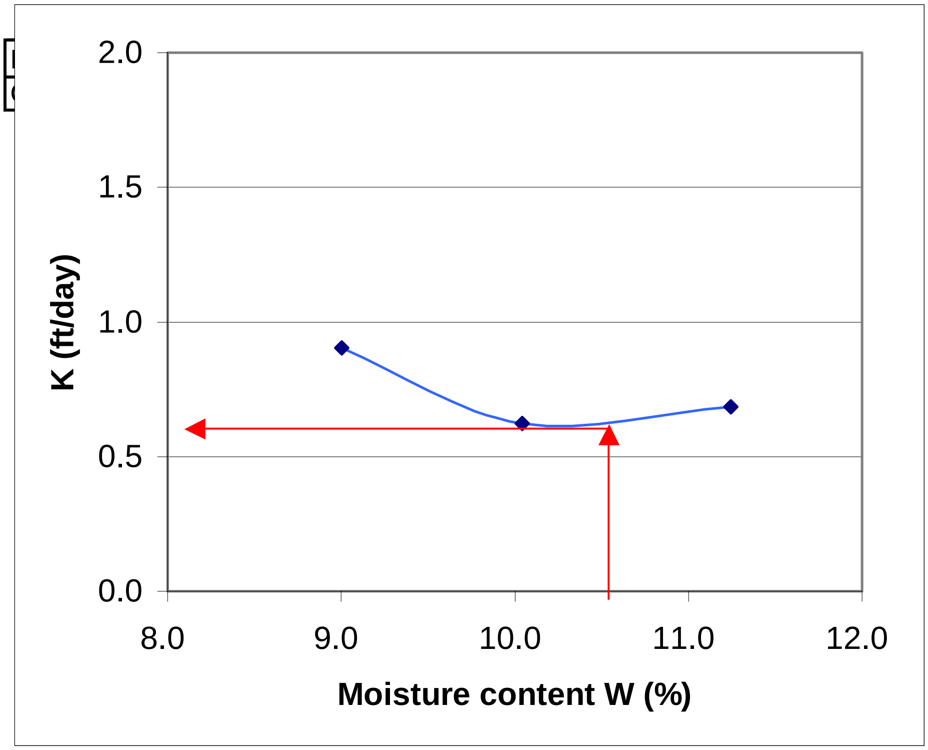


Figure A.22 Permeability Vs Moisture Content, District 2 (April).

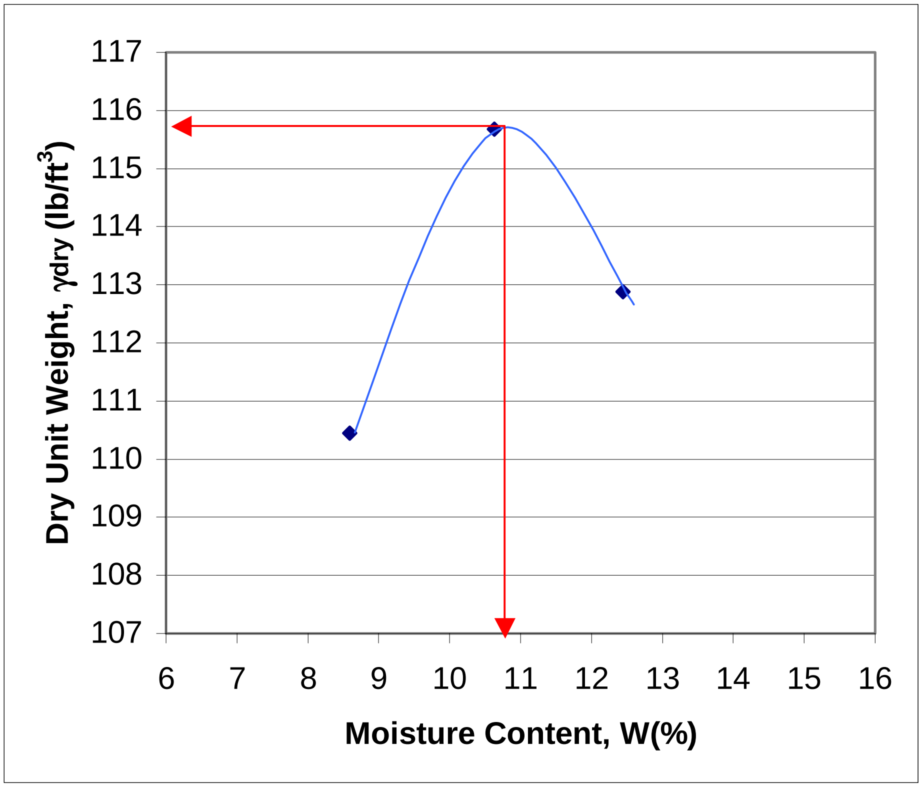


Figure A.23 Dry Unit Weight Vs Moisture Content, District 2 (May).

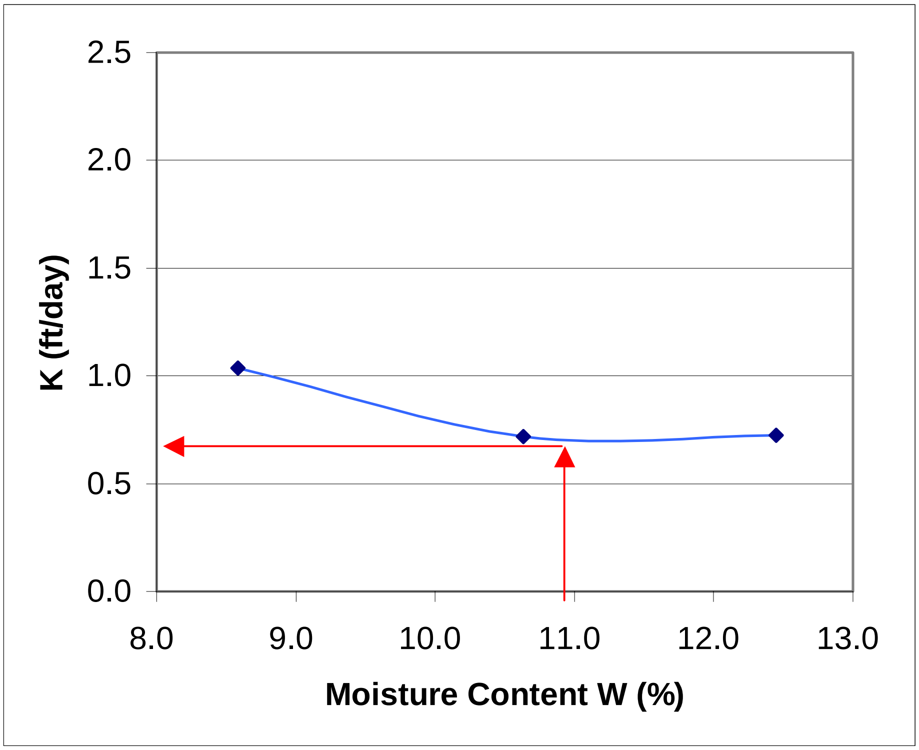


Figure A.24 Permeability Vs Moisture Content, District 2 (May).

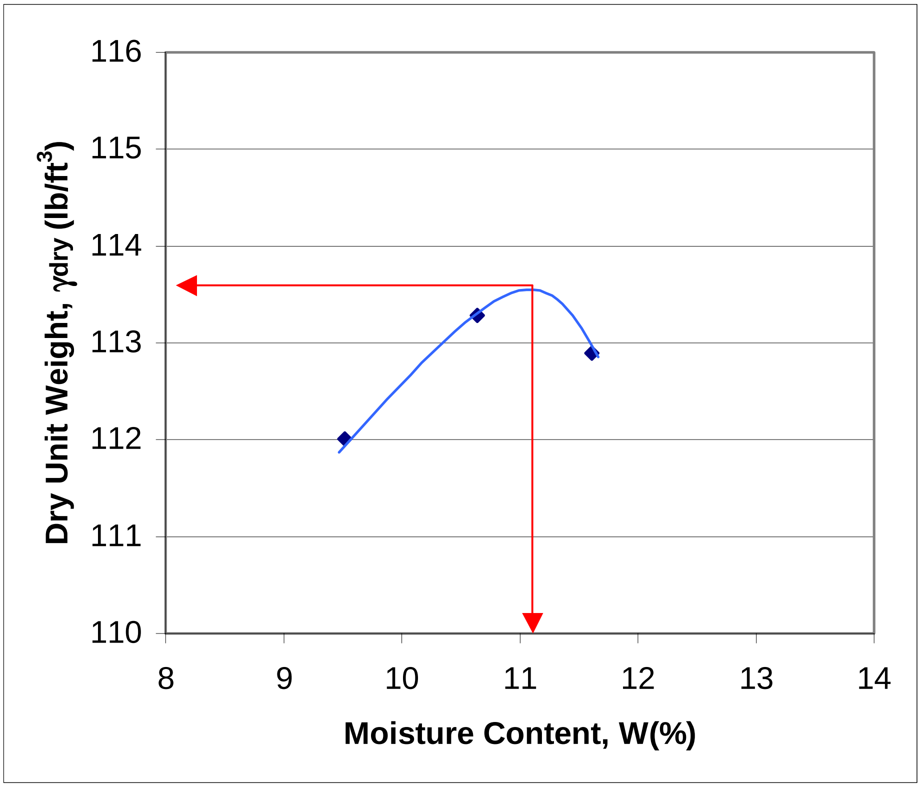


Figure A.25 Dry Unit Weight Vs Moisture Content, District 5 (December).

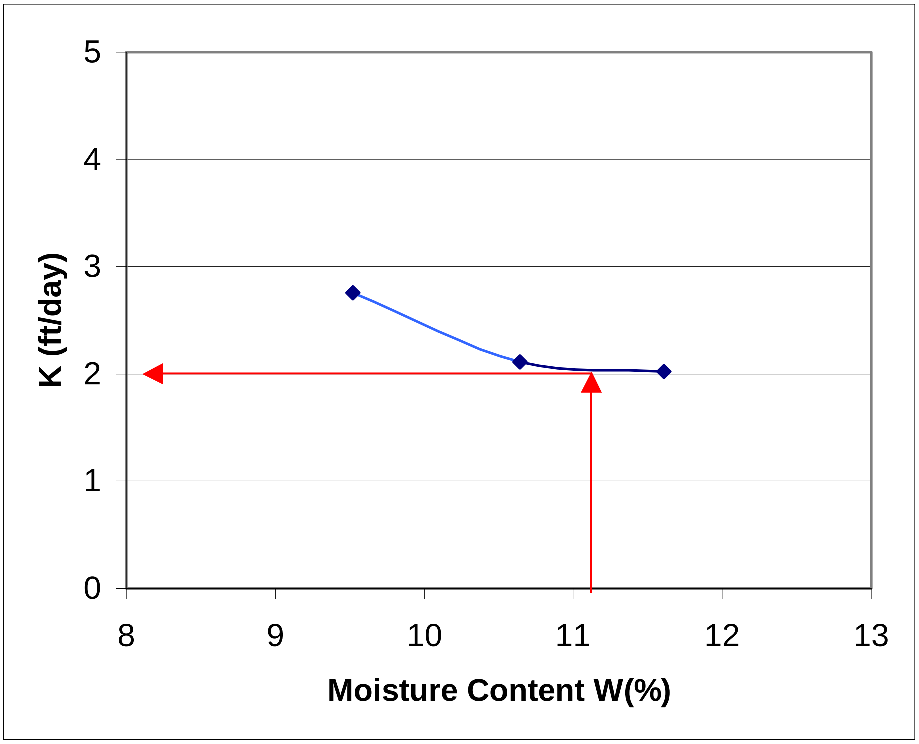


Figure A.26 Permeability Vs Moisture Content, District 5 (December).

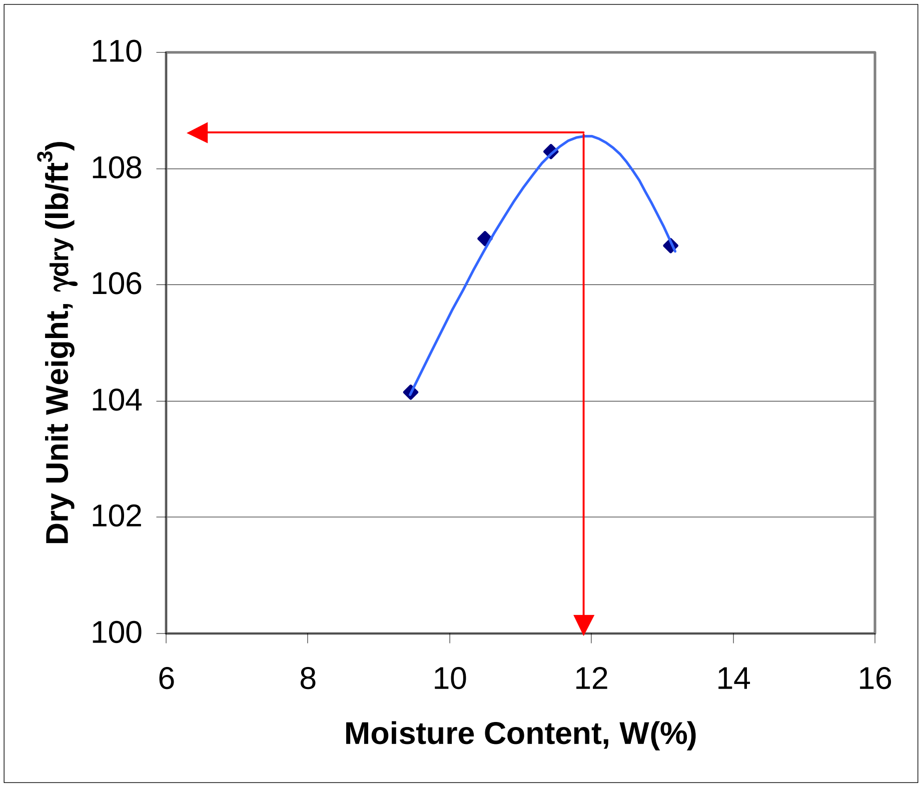


Figure A.27 Dry Unit Weight Vs Moisture Content, District 5 (January).

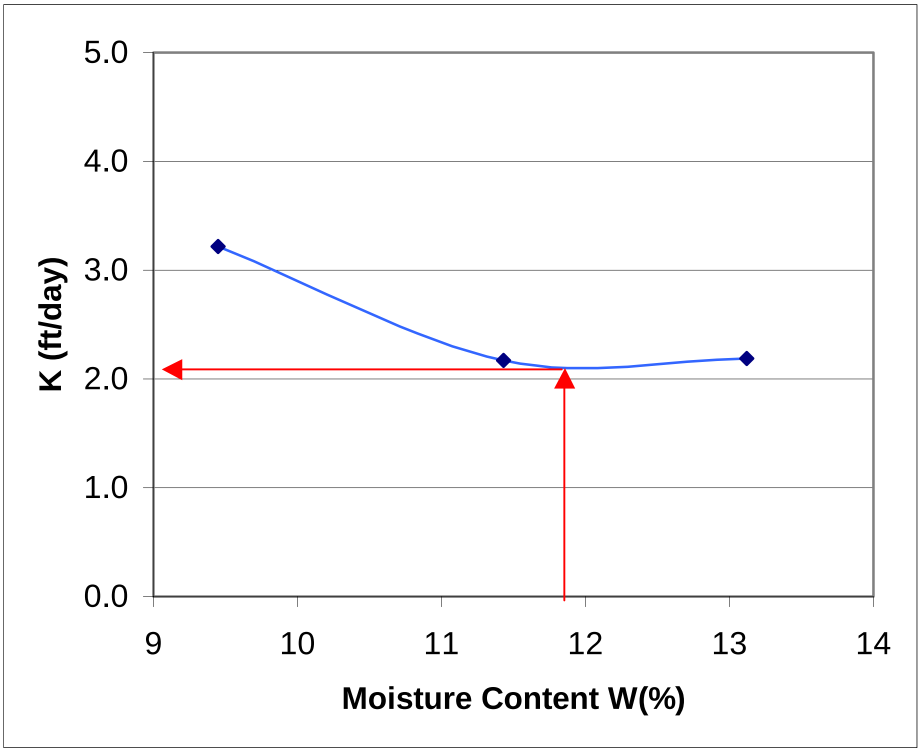


Figure A.28 Permeability Vs Moisture Content, District 5 (January).

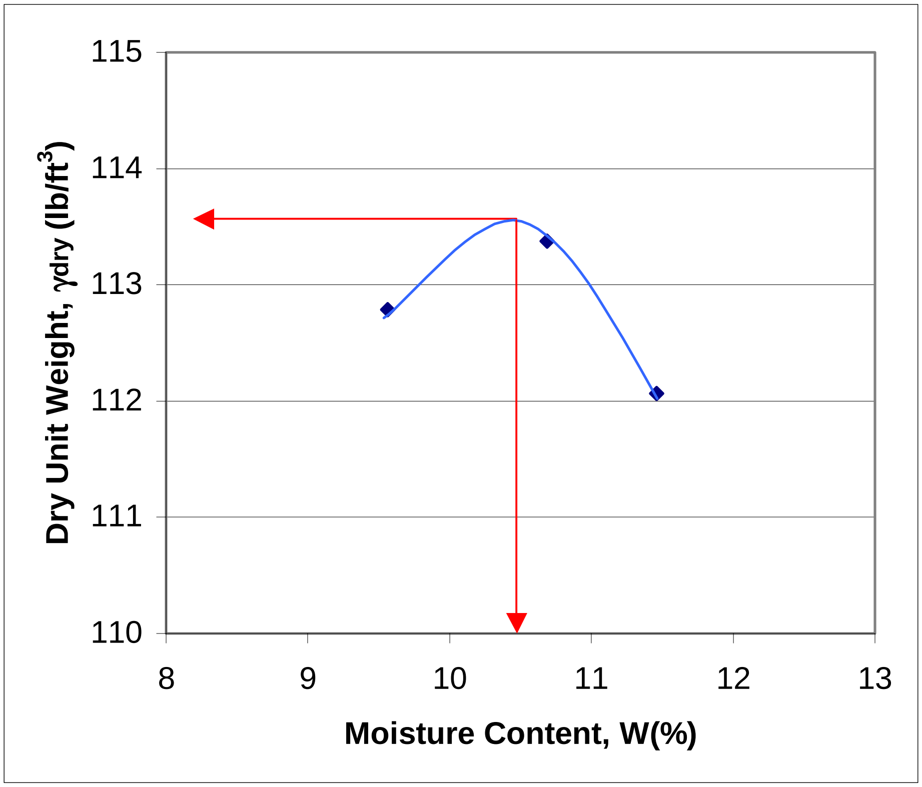


Figure A.29 Dry Unit Weight Vs Moisture Content, District 5 (February).

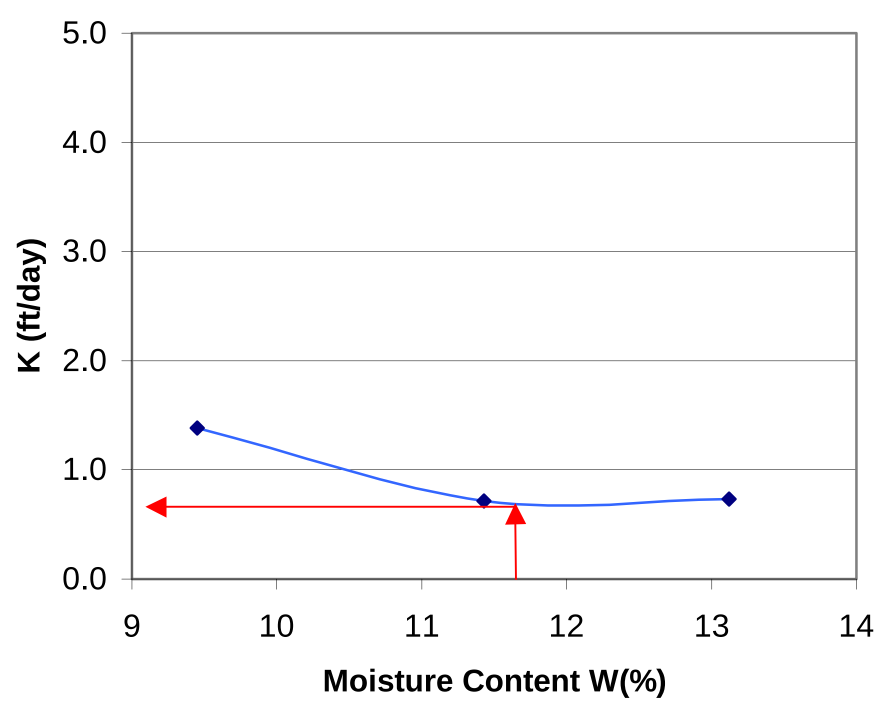


Figure A.30 Permeability Vs Moisture Content, District 5 (February).

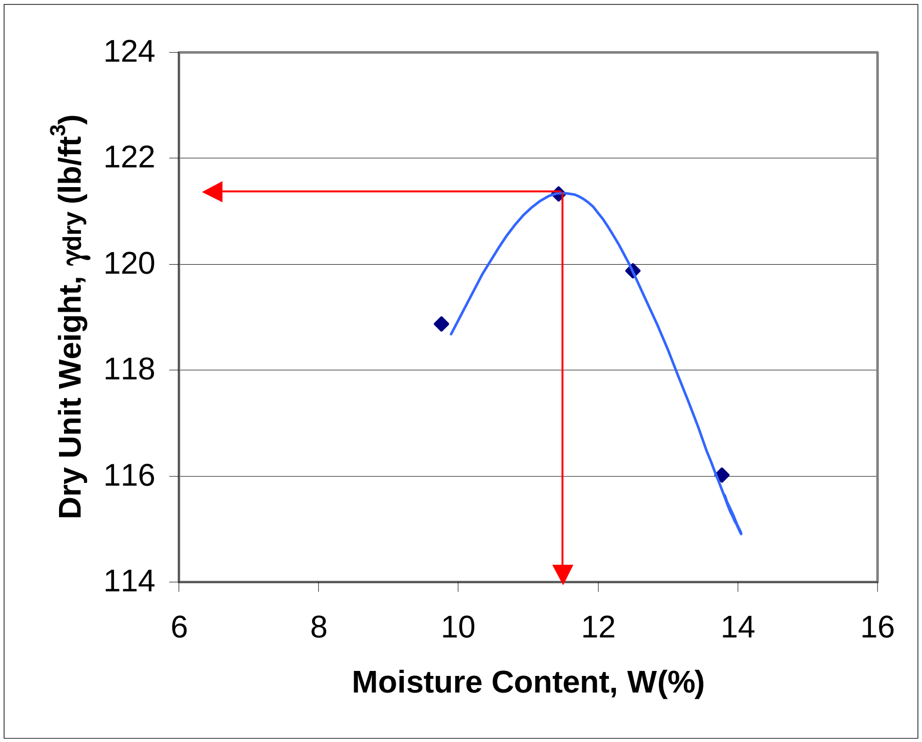


Figure A.31 Dry Unit Weight Vs Moisture Content, District 5 (June).

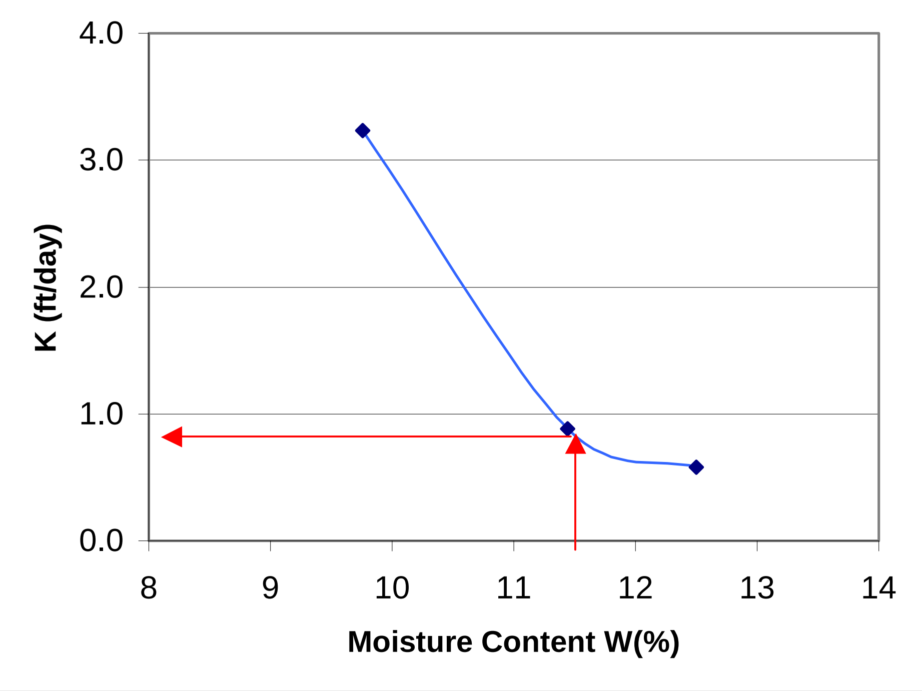


Figure A.32 Permeability Vs Moisture Content, District 5 (June).

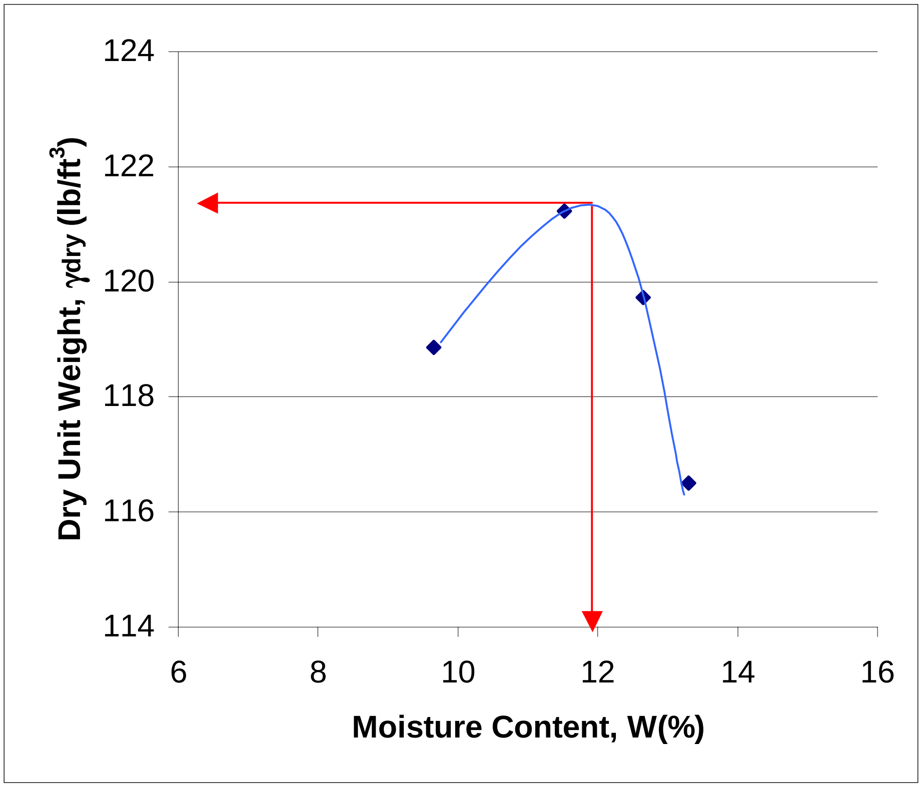
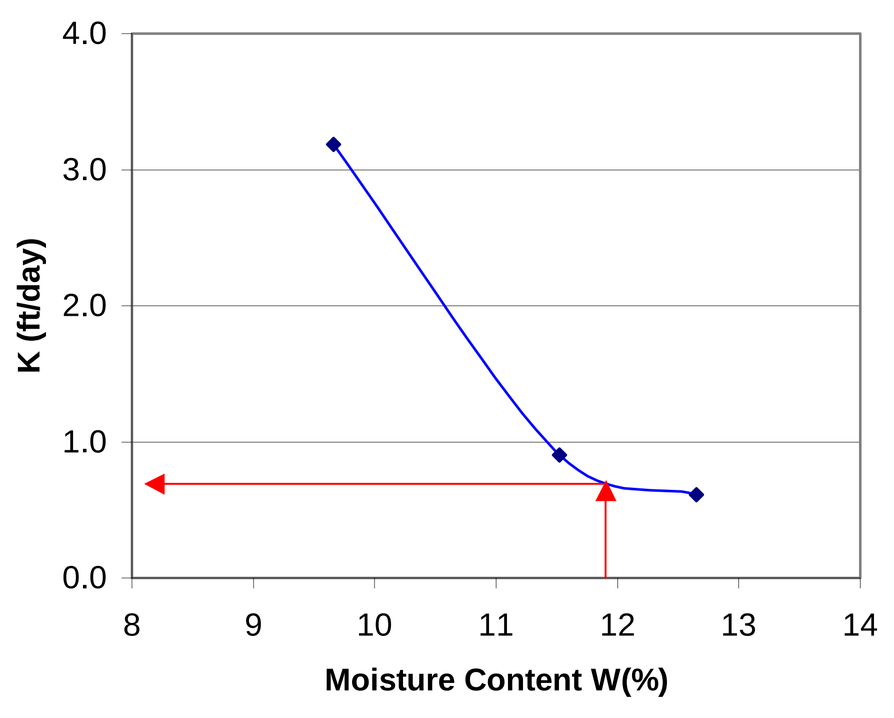


Figure A.33 Dry Unit Weight Vs Moisture Content, District 5 (July).



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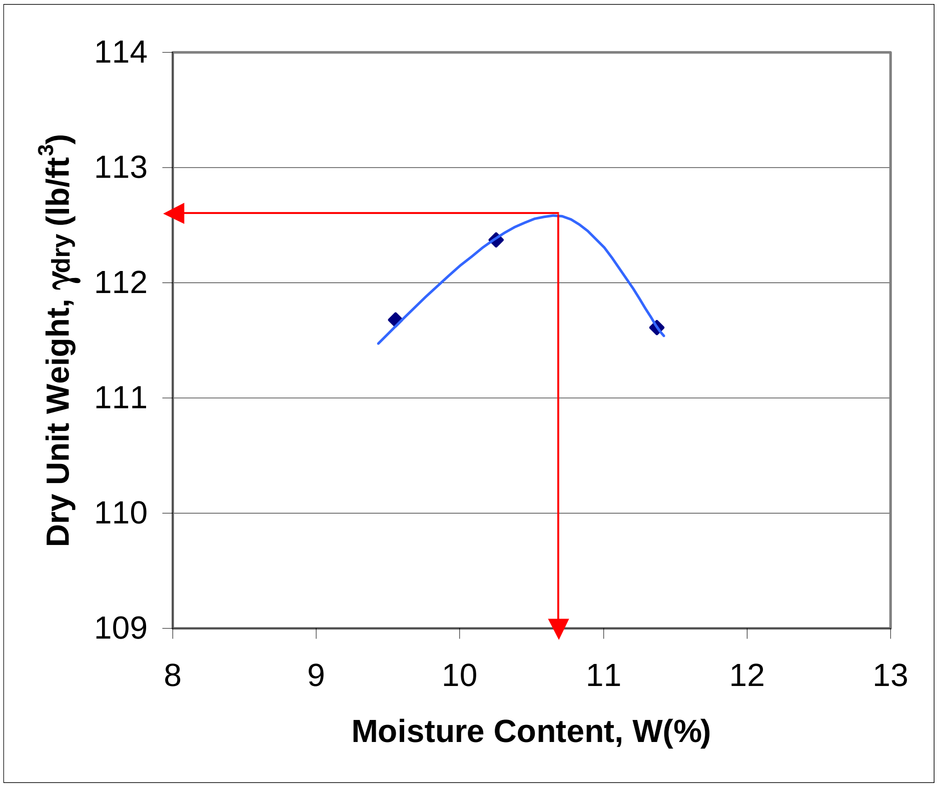


Figure A.35 Dry Unit Weight Vs Moisture Content, District 7 (December).

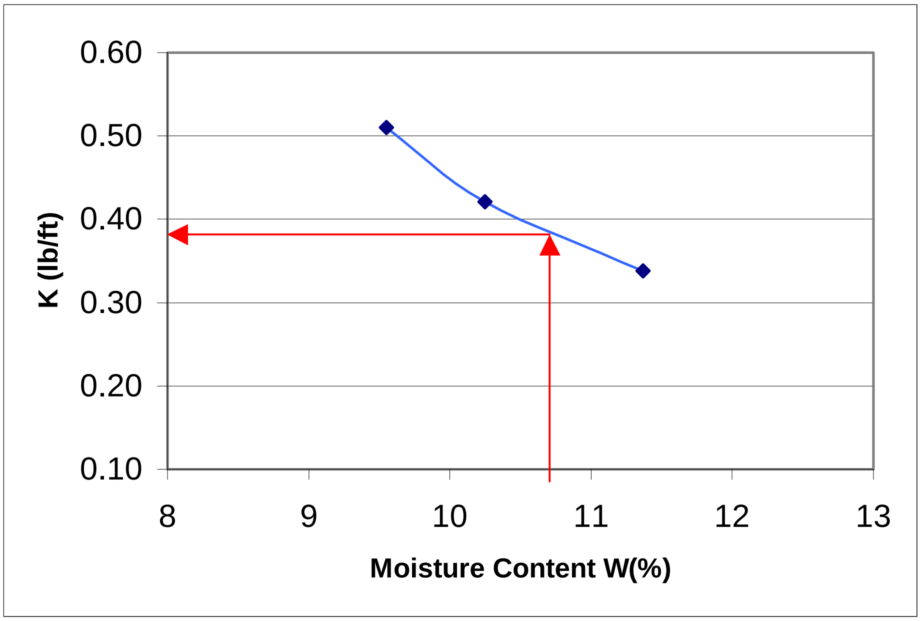


Figure A.36 Permeability Vs Moisture Content, District 7 (December).

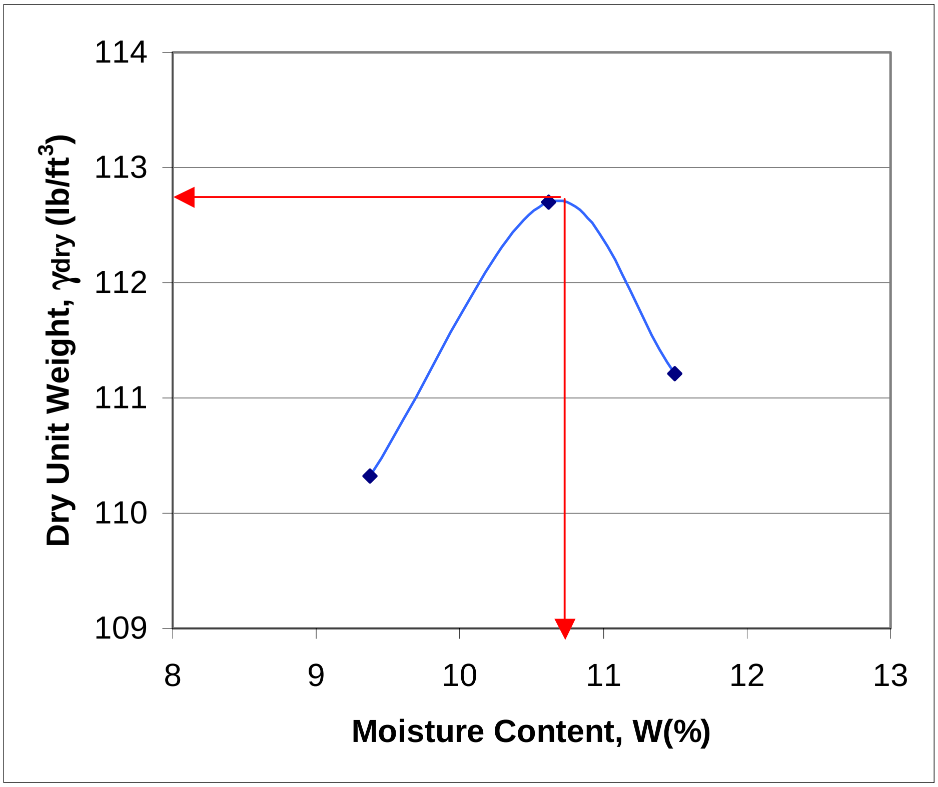
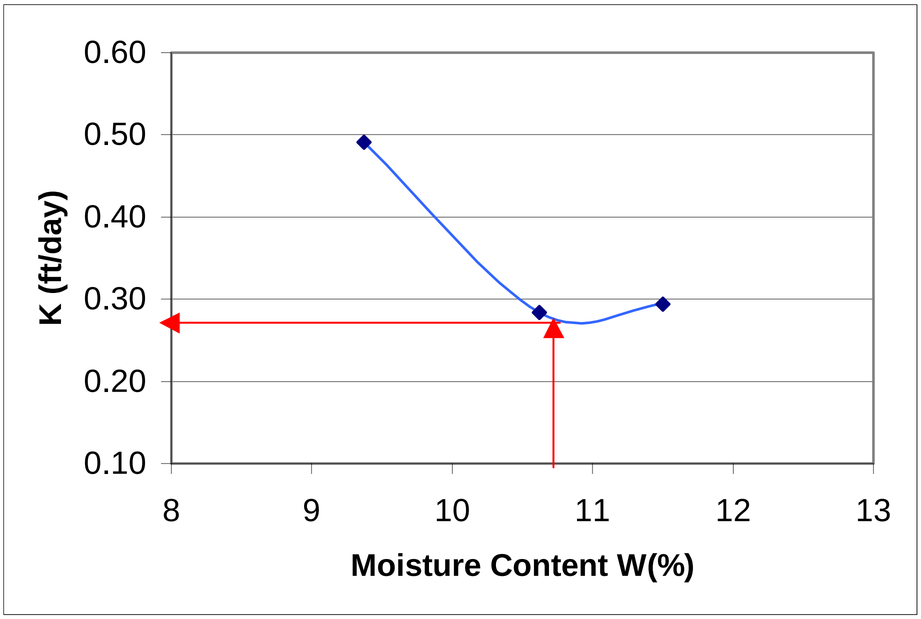


Figure A.37 Dry Unit Weight Vs Moisture Content, District 7 (January).



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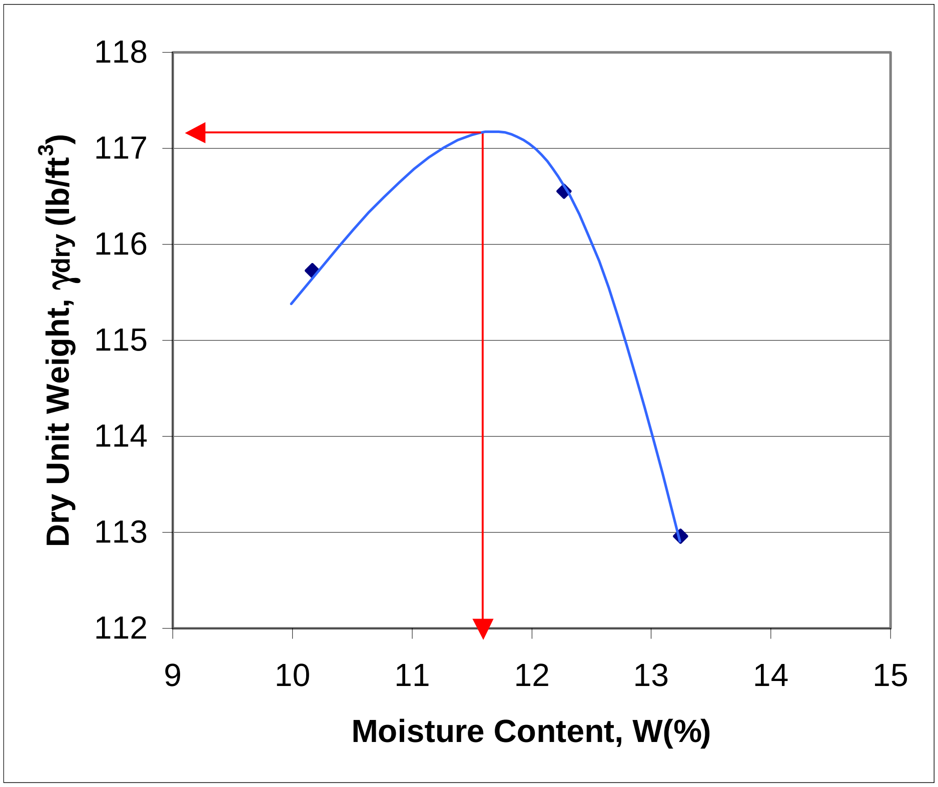

Figure A.39 Dry Unit Weight Vs Moisture Content, District 7 (February).

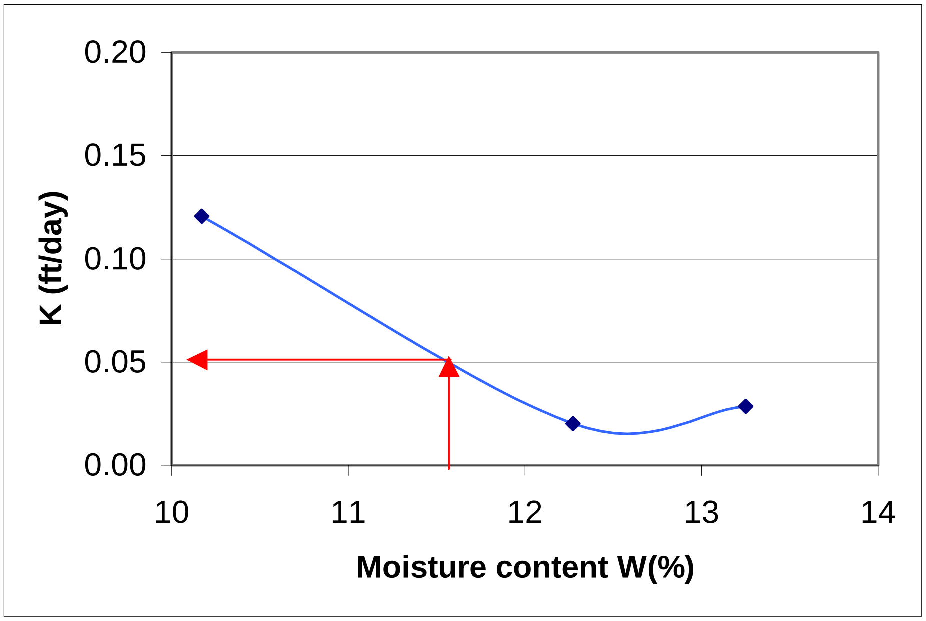

Figure A.40 Permeability Vs Moisture Content, District 7 (February).

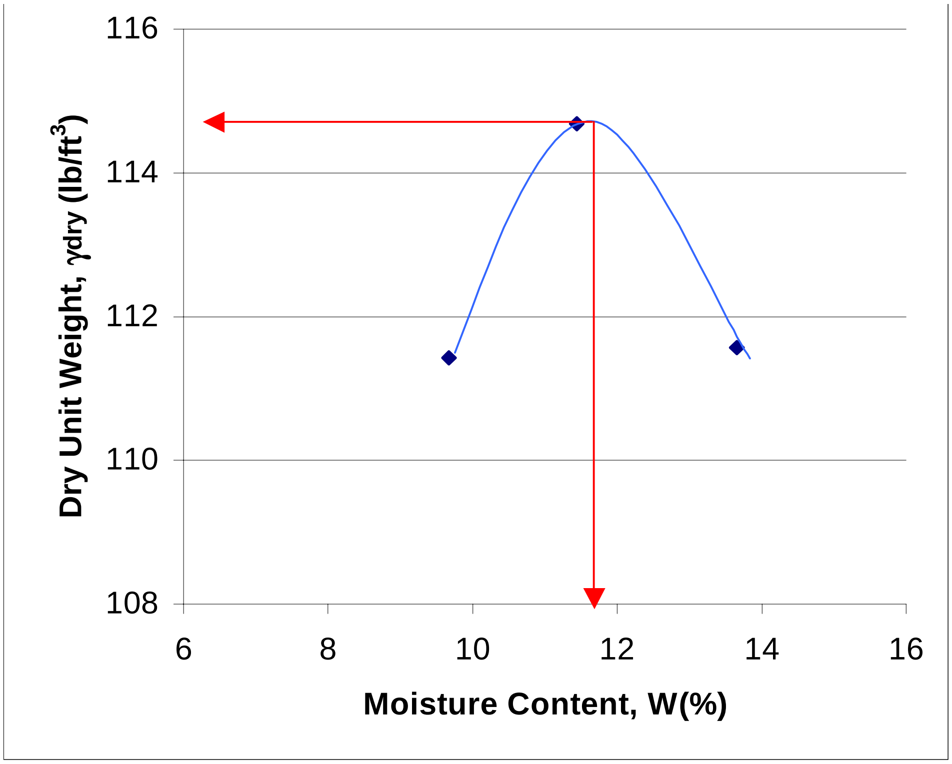

Figure A.41 Dry Unit Weight Vs Moisture Content Palm Beach, sample B (7-13-00).

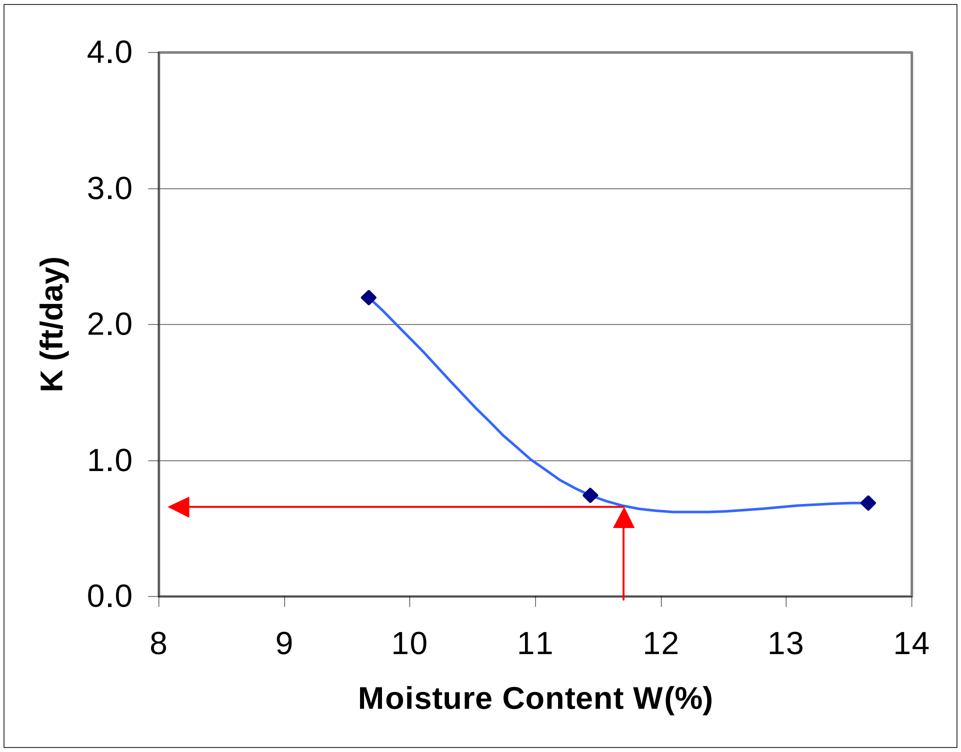

Figure A.42 Dry Unit Weight Vs Moisture Content Palm Beach, sample B (7-13-00).

APPENDIX B

CATT TIME-LOG

University of Central Florida

CATT Log

Day	Date	Starting Milage	Starting Time (H:M)	Ending Milage	Ending Time (H:M)	Daily Milage	Daily Load Reps.	Running Time (H:M)	Aveg. Velocity	Acc. Milage	Acc. Load Reps.
1	5-Sep-00	8,873.3	11:00 AM	8,884.2	1:05 PM	10.9	1,099.2	2:05	5.23	10.9	1,099.2
2	6-Sep-00	8,884.2	9:27 AM	8,919.0	12:25 PM	34.8	3,509.2	2:58	11.73	45.7	4,608.4
3	7-Sep-00	8,919.0	10:22 AM	8,965.0	2:00 PM	46.0	4,638.7	3:38	12.66	91.7	9,247.1
4	8-Sep-00	8,965.0	9:49 AM	8,997.5	12:27 PM	32.5	3,277.3	2:38	12.34	124.2	12,524.4
5	11-Sep-00	8,997.5	9:48 AM	9,038.7	1:21 PM	41.2	4,154.6	3:33	11.61	165.4	16,679.0
6	12-Sep-00	9,038.7	9:25 AM	9,043.0	9:50 AM	4.3	433.6	0:25	10.32	169.7	17,112.6
6	12-Sep-00	9,043.0	9:56 AM	9,078.8	12:51 PM	35.8	3,610.1	2:55	12.27	205.5	20,722.7
6	12-Sep-00	9,078.8	1:57 PM	9,109.6	4:31 PM	30.8	3,105.9	2:34	12.00	236.3	23,828.6
7	13-Sep-00	9,109.6	10:04 AM	9,141.1	1:06 PM	31.5	3,176.5	3:02	10.38	267.8	27,005.0
8	14-Sep-00	9,141.1	9:50 AM	9,171.0	12:53 PM	29.9	3,015.1	3:03	9.80	297.7	30,020.2
9	18-Sep-00	9,171.0	9:39 AM	9,172.7	9:49 AM	1.7	171.4	0:10	10.20	299.4	30,191.6
9	18-Sep-00	9,172.7	1:28 PM	9,198.0	3:31 PM	25.3	2,551.3	2:03	12.34	324.7	32,742.9
10	19-Sep-00	9,198.0	9:05 AM	9,225.4	12:10 PM	27.4	2,763.0	3:05	8.89	352.1	35,505.9
11	20-Sep-00	9,225.4	9:42 AM	9,256.2	1:18 PM	30.8	3,105.9	3:36	8.56	382.9	38,611.8
12	21-Sep-00	9,256.2	9:34 AM	9,280.0	12:13 PM	23.8	2,400.0	2:39	8.98	406.7	41,011.8
12	21-Sep-00	9,280.0	1:29 PM	9,309.6	4:47 PM	29.6	2,984.9	3:18	8.97	436.3	43,996.6
13	22-Sep-00	9,309.6	9:19 AM	9,335.2	12:17 PM	25.6	2,581.5	2:58	8.63	461.9	46,578.2
13	22-Sep-00	9,335.2	1:24 PM	9,382.6	5:49 PM	47.4	4,779.8	4:25	10.73	509.3	51,358.0
14	25-Sep-00	9,382.6	9:18 AM	9,473.3	6:00 PM	90.7	9,146.2	8:42	10.43	600.0	60,504.2
15	26-Sep-00	9,473.3	8:53 AM	9,505.9	11:59 AM	32.6	3,287.4	3:06	10.52	632.6	63,791.6
16	29-Sep-00	9,505.9	9:38 AM	9,532.8	12:16 PM	26.9	2,712.6	2:38	10.22	659.5	66,504.2
17	2-Oct-00	9,532.8	9:25 AM	9,562.4	12:27 PM	29.6	2,984.9	3:02	9.76	689.1	69,489.1
18	3-Oct-00	9,562.4	9:28 AM	9,588.6	1:26 PM	26.2	2,642.0	3:58	6.61	715.3	72,131.1
19	4-Oct-00	9,588.6	9:48 AM	9,621.4	1:46 PM	32.8	3,307.6	3:58	8.27	748.1	75,438.7
20	5-Oct-00	9,621.4	11:10 AM	9,646.7	1:44 PM	25.3	2,551.3	2:34	9.86	773.4	77,989.9
20	5-Oct-00	9,646.7	2:30 PM	9,689.9	6:44 PM	43.2	4,356.3	4:14	10.20	816.6	82,346.2
21	9-Oct-00	9,689.9	9:23 AM	9,737.2	1:55 PM	47.3	4,769.7	4:32	10.43	863.9	87,116.0
22	10-Oct-00	9,737.2	9:45 AM	9,761.9	12:48 PM	24.7	2,490.8	3:03	8.10	888.6	89,606.7
23	11-Oct-00	9,761.9	9:28 AM	9,785.2	11:42 AM	23.3	2,349.6	2:14	10.43	911.9	91,956.3
23						**39.6**	**3,998.1**	**91.10**	**10.02**	**911.9**	**91,956.3**

University of Central Florida

CATT Log

Day	Date	Starting Milage	Starting Time (H:M)	Ending Milage	Ending Time (H:M)	Daily Milage	Daily Load Reps.	Running Time (H:M)	Aveg. Velocity	Acc. Milage	Acc. Load Reps.
24	12-Oct-00	9,785.2	9:55 AM	9,795.6	11:20 AM	10.4	1,048.7	1:25	7.34	922.3	93,005.0
25	13-Oct-00	9,795.6	8:58 AM	9,818.7	11:32 AM	23.1	2,329.4	2:34	9.00	945.4	95,334.5
26	16-Oct-00	9,818.7	9:19 AM	9,873.3	2:31 PM	54.6	5,505.9	5:12	10.50	1,000.0	100,840.3
27	17-Oct-00	9,873.3	9:28 AM	9,897.5	12:01 PM	24.2	2,440.3	2:33	9.49	1,024.2	103,280.7
28	19-Oct-00	9,897.5	9:24 AM	9,930.8	12:44 PM	33.3	3,358.0	3:20	9.99	1,057.5	106,638.7
29	20-Oct-00	9,930.8	11:44 AM	9,949.0	2:10 PM	18.2	1,835.3	2:26	7.48	1,075.7	108,473.9
30	23-Oct-00	9,949.0	9:23 AM	9,978.2	12:20 PM	29.2	2,944.5	2:57	9.90	1,104.9	111,418.5
31	24-Oct-00	9,978.2	9:31 AM	10,006.0	12:18 PM	27.8	2,803.4	2:47	9.99	1,132.7	114,221.8
32	25-Oct-00	10,006.0	9:24 AM	10,035.6	12:28 PM	29.6	2,984.9	3:04	9.65	1,162.3	117,206.7
33	26-Oct-00	10,035.6	9:25 AM	10,058.3	11:39 AM	22.7	2,289.1	2:14	10.16	1,185.0	119,495.8
34	30-Oct-00	10,058.3	9:01 AM	10,101.6	1:47 PM	43.3	4,366.4	4:46	9.08	1,228.3	123,862.2
35	31-Oct-00	10,101.6	8:29 AM	10,126.1	11:58 AM	24.5	2,470.6	3:29	7.03	1,252.8	126,332.8
36	1-Nov-00	10,126.1	8:24 AM	10,137.2	9:46 AM	11.1	1,119.3	1:22	8.12	1,263.9	127,452.1
36	1-Nov-00	10,137.2	10:02 AM	10,160.8	12:41 PM	23.6	2,379.8	2:39	8.91	1,287.5	129,831.9
37	3-Nov-00	10,160.8	9:14 AM	10,192.5	12:54 PM	31.7	3,196.6	3:40	8.65	1,319.2	133,028.6
38	6-Nov-00	10,192.5	8:24 AM	10,257.8	2:47 PM	65.3	6,584.9	6:23	10.23	1,384.5	139,613.4
39	7-Nov-00	10,257.8	8:29 AM	10,285.8	11:35 AM	28.0	2,823.5	3:06	9.03	1,412.5	142,437.0
40	8-Nov-00	10,285.8	8:32 AM	10,315.7	11:41 AM	29.9	3,015.1	3:09	9.49	1,442.4	145,452.1
41	9-Nov-00	10,315.7	8:39 AM	10,344.5	11:55 AM	28.8	2,904.2	3:16	8.82	1,471.2	148,356.3
42	13-Nov-00	10,344.5	8:35 AM	10,374.9	12:13 PM	30.4	3,065.5	3:38	8.37	1,501.6	151,421.8
42	13-Nov-00	10,374.9	2:21 PM	10,386.1	3:34 PM	11.2	1,129.4	1:13	9.21	1,512.8	152,551.3
43	15-Nov-00	10,386.1	8:33 AM	10,397.6	9:45 AM	11.5	1,159.7	1:12	9.58	1,524.3	153,710.9
43	15-Nov-00	10,397.6	10:02 AM	10,419.6	12:11 PM	22	2,218.5	2:09	10.23	1,546.3	155,929.4
43	15-Nov-00	10,419.6	1:18 PM	10,440.0	3:27 PM	20.4	2,057.1	2:09	9.49	1,566.7	157,986.6
44	16-Nov-00	10,440.0	8:33 AM	10,472.4	11:57 AM	32.4	3,267.2	3:24	9.53	1,599.1	161,253.8
45	17-Nov-00	10,472.4	8:26 AM	10,505.2	11:53 AM	32.8	3,307.6	3:27	9.51	1,631.9	164,561.3
46	21-Nov-00	10,505.2	8:38 AM	10,515.3	9:50 AM	10.1	1,018.5	1:12	8.42	1,642.0	165,579.8
47	22-Nov-00	10,515.3	9:40 AM	10,543.4	12:57 PM	28.1	2,833.6	3:17	8.56	1,670.1	168,413.4
48	27-Nov-00	10,543.4	8:28 AM	10,595.4	1:38 PM	52.0	5,243.7	5:10	10.06	1,722.1	173,657.1

48								**87.22**	**9.17**	**1,722.1**	**173,657.1**

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CATT Log

Day	Date	Starting Milage	Starting Time (H:M)	Ending Milage	Ending Time (H:M)	Daily Milage	Daily Load Reps.	Running Time (H:M)	Aveg. Velocity	Acc. Milage	Acc. Load Reps.
49	28-Nov-00	10,595.4	9:35 AM	10,613.5	11:55 AM	18.1	1,825.2	2:20	7.76	1,740.2	175,482.4
50	29-Nov-00	10,613.5	8:39 AM	10,650.8	12:41 PM	37.3	3,761.3	4:02	9.25	1,777.5	179,243.7
51	1-Dec-00	10,650.8	8:50 AM	10,666.6	10:38 AM	15.8	1,593.3	1:48	8.78	1,793.3	180,837.0
51	1-Dec-00	10,666.6	10:40 AM	10,667.1	10:48 AM	0.5	50.4	0:08	3.75	1,793.8	180,887.4
51	1-Dec-00	10,667.1	10:51 AM	10,740.9	5:57 PM	73.8	7,442.0	7:06	10.39	1,867.6	188,329.4
52	4-Dec-00	10,740.9	8:41 AM	10,743.6	8:55 AM	2.7	272.3	0:14	11.57	1,870.3	188,601.7
52	4-Dec-00	10,743.6	9:00 AM	10,782.1	12:37 PM	38.5	3,882.4	3:37	10.65	1,908.8	192,484.0
52	4-Dec-00	10,782.1	1:43 PM	10,822.0	5:40 PM	39.9	4,023.5	3:57	10.10	1,948.7	196,507.6
53	5-Dec-00	10,822.0	10:00 AM	10,845.2	12:35 PM	23.2	2,339.5	2:35	8.98	1,971.9	198,847.1
54	6-Dec-00	10,845.2	9:00 AM	10,874.2	12:02 PM	29.0	2,924.4	3:02	9.56	2,000.9	201,771.4
55	8-Dec-00	10,874.2	9:35 AM	10,895.6	12:05 PM	21.4	2,158.0	2:30	8.56	2,022.3	203,929.4
55	8-Dec-00	10,895.6	3:17 PM	10,919.5	5:44 PM	23.9	2,410.1	2:27	9.76	2,046.2	206,339.5
56	11-Dec-00	10,919.5	9:05 AM	10,964.0	1:14 PM	44.5	4,487.4	4:09	10.72	2,090.7	210,826.9
57	12-Dec-00	10,964.0	11:05 AM	10,983.7	1:02 PM	19.7	1,986.6	1:57	10.10	2,110.4	212,813.4
58	13-Dec-00	10,983.7	9:10 AM	11,018.9	1:15 PM	35.2	3,549.6	4:05	8.62	2,145.6	216,363.0
58	13-Dec-00	11,018.9	2:25 PM	11,044.5	5:07 PM	25.6	2,581.5	2:42	9.48	2,171.2	218,944.5
59	15-Dec-00	11,044.5	9:20 AM	11,093.5	2:14 PM	49.0	4,941.2	4:54	10.00	2,220.2	223,885.7
60	18-Dec-00	11,093.5	8:54 AM	11,121.0	11:42 AM	27.5	2,773.1	2:48	9.82	2,247.7	226,658.8
60	18-Dec-00	11,121.0	1:22 PM	11,161.6	5:15 PM	40.6	4,094.1	3:53	10.45	2,288.3	230,752.9
61	19-Dec-00	11,161.6	9:25 AM	11,189.9	12:46 PM	28.3	2,853.8	3:21	8.45	2,316.6	233,606.7
61	19-Dec-00	11,189.9	2:54 PM	11,204.4	4:32 PM	14.5	1,462.2	1:38	8.88	2,331.1	235,068.9
62	21-Dec-00	11,204.4	9:25 AM	11,251.5	2:16 PM	47.1	4,749.6	4:51	9.71	2,378.2	239,818.5
63	22-Dec-00	11,251.5	7:45 AM	11,287.6	11:29 AM	36.1	3,640.3	3:44	9.67	2,414.3	243,458.8
64	28-Dec-00	11,287.6	12:40 PM	11,301.8	2:47 PM	14.2	1,431.9	2:07	6.71	2,428.5	244,890.8
65	3-Jan-01	11,301.8	9:07 AM	11,324.7	11:42 AM	22.9	2,309.2	2:35	8.86	2,451.4	247,200.0
66	4-Jan-01	11,324.7	9:30 AM	11,371.2	1:56 PM	46.5	4,689.1	4:26	10.49	2,497.9	251,889.1
66	4-Jan-01	11,371.2	3:02 PM	11,394.5	5:14 PM	23.3	2,349.6	2:12	10.59	2,521.2	254,238.7

67	5-Jan-01	11,394.5	10:30 AM	11,412.8	12:25 PM	18.3	1,845.4	1:55	9.55	2,539.5	256,084.0
68	8-Jan-01	11,412.8	9:23 AM	11,450.1	1:14 PM	37.3	3,761.3	3:51	9.69	2,576.8	259,845.4
68								**88.90**	**9.34**	**2,576.8**	**259,845.4**

University of Central Florida

CATT Log

Day	Date	Starting Milage	Starting Time (H:M)	Ending Milage	Ending Time (H:M)	Daily Milage	Daily Load Reps.	Running Time (H:M)	Aveg. Velocity	Acc. Milage	Acc. Load Reps.
69	8-Jan-01	11,450.1	4:13 PM	11,468.1	6:02 PM	18.0	1,815.1	1:49	9.91	2,594.8	261,660.5
70	10-Jan-01	11,468.1	9:35 AM	11,492.6	12:35 PM	24.5	2,470.6	3:00	8.17	2,619.3	264,131.1
71	12-Jan-01	11,492.6	8:41 AM	11,540.9	1:20 PM	48.3	4,870.6	4:39	10.39	2,667.6	269,001.7
72	29-Jan-01	11,540.9	1:52 PM	11,592.0	6:17 PM	51.1	5,152.9	4:25	11.57	2,718.7	274,154.6
73	31-Jan-01	11,592.0	10:10 AM	11,621.1	1:47 PM	29.1	2,934.5	3:37	8.05	2,747.8	277,089.1
73	31-Jan-01	11,621.1	2:36 PM	11,652.7	5:27 PM	31.6	3,186.6	2:51	11.09	2,779.4	280,275.6
73	31-Jan-01	11,652.7	6:01 PM	11,656.7	6:23 PM	4.0	403.4	0:22	10.91	2,783.4	280,679.0
74	2-Feb-01	11,656.7	9:00 AM	11,700.3	1:45 PM	43.6	4,396.6	4:45	9.18	2,827.0	285,075.6
74	2-Feb-01	11,700.3	9:40 AM	11,723.7	12:40 PM	23.4	2,359.7	3:00	7.80	2,850.4	287,435.3
75	5-Feb-01	11,723.7	5:38 PM	11,733.2	6:32 PM	9.5	958.0	0:54	10.56	2,859.9	288,393.3
76	6-Feb-01	11,733.2	9:40 AM	11,764.9	1:45 PM	31.7	3,196.6	4:05	7.76	2,891.6	291,589.9
77	7-Feb-01	11,764.9	9:35 AM	11,800.0	2:00 PM	35.1	3,539.5	4:25	7.95	2,926.7	295,129.4
77	7-Feb-01	11,800.0	4:40 PM	11,806.2	5:14 PM	6.2	625.2	0:34	10.94	2,932.9	295,754.6
78	16-Feb-01	11,806.2	10:00 AM	11,840.8	2:20 PM	34.6	3,489.1	4:20	7.98	2,967.5	299,243.7
79	19-Feb-01	11,840.8	4:30 PM	11,861.3	6:38 PM	20.5	2,067.2	2:08	9.61	2,988.0	301,310.9
80	21-Feb-01	11,861.3	2:20 PM	11,893.2	6:20 PM	31.9	3,216.8	4:00	7.98	3,019.9	304,527.7
81	22-Feb-01	11,893.2	10:15 AM	11,923.6	2:05 PM	30.4	3,065.5	3:50	7.93	3,050.3	307,593.3
82	23-Feb-01	11,923.6	9:45 AM	11,958.6	2:30 PM	35.0	3,529.4	4:45	7.37	3,085.3	311,122.7
82	23-Feb-01	11,958.6	3:32 PM	11,964.0	4:11 PM	5.4	544.5	0:39	8.31	3,090.7	311,667.2
83	26-Feb-01	11,964.0	10:00 AM	12,000.4	2:05 PM	36.4	3,670.6	4:05	8.91	3,127.1	315,337.8
84	27-Feb-01	12,000.4	10:30 AM	12,029.1	2:15 PM	28.7	2,894.1	3:45	7.65	3,155.8	318,231.9
85	28-Feb-01	12,029.1	10:00 AM	12,053.9	1:30 PM	24.8	2,500.8	3:30	7.09	3,180.6	320,732.8
85	28-Feb-01	12,053.9	4:38 PM	12,066.3	6:21 PM	12.4	1,250.4	1:43	7.22	3,193.0	321,983.2
86	1-Mar-01	12,066.3	12:30 PM	12,077.9	2:06 PM	11.6	1,169.7	1:36	7.25	3,204.6	323,152.9
87	5-Mar-01	12,077.9	9:35 AM	12,081.4	10:10 AM	3.5	352.9	0:35	6.00	3,208.1	323,505.9

87	5-Mar-01	12,081.4	10:30 AM	12,091.9	12:00 PM	10.5	1,058.8	1:30	7.00	3,218.6	324,564.7
87	5-Mar-01	12,091.9	3:52 PM	12,112.5	6:39 PM	20.6	2,077.3	2:47	7.40	3,239.2	326,642.0
88	8-Mar-01	12,112.5	9:35 AM	12,150.4	2:15 PM	37.9	3,821.8	4:40	8.12	3,277.1	330,463.9
89	14-Mar-01	12,150.4	9:45 AM	12,161.3	11:35 PM	10.9	1,099.2	13:50	0.79	3,288.0	331,563.0
								96.15	**8.31**	**3,288.0**	**331,563.0**

University of Central Florida

CATT Log

Day	Date	Starting Milage	Starting Time (H:M)	Ending Milage	Ending Time (H:M)	Daily Milage	Daily Load Reps.	Running Time (H:M)	Aveg. Velocity	Acc. Milage	Acc. Load Reps.
89	14-Mar-01	12,161.3	11:55 AM	12,174.4	2:30 PM	13.1	1,321.0	2:35	5.07	3,290.2	331,784.9
90	15-Mar-01	12,174.4	9:15 AM	12,179.9	10:45 AM	5.5	554.6	1:30	3.67	3,295.7	332,339.5
90	15-Mar-01	12,179.9	12:25 PM	12,197.5	2:50 PM	17.6	1,774.8	2:25	7.28	3,313.3	334,114.3
91	16-Mar-01	12,197.5	10:30 AM	12,215.0	1:00 PM	17.5	1,764.7	2:30	7.00	3,330.8	335,879.0
92	19-Mar-01	12,215.0	11:15 AM	12,241.5	3:05 PM	26.5	2,672.3	3:50	6.91	3,357.3	338,551.3
92	19-Mar-01	12,241.5	4:25 PM	12,260.0	6:50 PM	18.5	1,865.5	2:25	7.66	3,375.8	340,416.8
93	20-Mar-01	12,260.0	8:50 AM	12,274.3	11:00 AM	14.3	1,442.0	2:10	6.60	3,390.1	341,858.8
94	21-Mar-01	12,274.3	10:15 AM	12,294.6	1:25 PM	20.3	2,047.1	3:10	6.41	3,410.4	343,905.9
94	21-Mar-01	12,294.6	3:51 PM	12,310.1	5:58 PM	15.5	1,563.0	2:07	7.32	3,425.9	345,468.9
95	23-Mar-01	12,310.1	9:30 AM	12,323.5	12:00 PM	13.4	1,351.3	2:30	5.36	3,439.3	346,820.2
95	23-Mar-01	12,323.5	3:17 PM	12,329.7	4:09 PM	6.2	625.2	0:52	7.15	3,445.5	347,445.4
96	26-Mar-01	12,329.7	10:45 AM	12,385.8	6:33 PM	56.1	5,657.1	7:48	7.19	3,501.6	353,102.5
97	27-Mar-01	12,385.8	10:00 AM	12,406.6	1:05 PM	20.8	2,097.5	3:05	6.75	3,522.4	355,200.0
98	28-Mar-01	12,406.6	4:05 PM	12,425.2	6:31 PM	18.6	1,875.6	2:26	7.64	3,541.0	357,075.6
99	30-Mar-01	12,425.2	10:15 AM	12,452.3	2:30 PM	27.1	2,732.8	4:15	6.38	3,568.1	359,808.4
100	2-Apr-01	12,452.3	5:04 PM	12,467.7	7:36 PM	15.4	1,552.9	2:32	6.08	3,583.5	361,361.3
101	6-Apr-01	12,467.7	10:00 AM	12,476.0	11:45 PM	8.3	837.0	13:45	0.60	3,591.8	362,198.3

	59.92	**6.18**	**3,591.8**	**362,198.3**

APPENDIX C

FWD Raw Data

```
R80                                        109 00082570UCF82536F10       2000
700031008002-03165620                      328           8
                        150                  0          203    305     457     610     914    1524    5.9
A:\
UCF                         TEST                TRACK
S                           12.0000WBOW45               110    113 Heights  ...........................
S                           12.0000WBOW45               110    113 Heights  ...........................
0'                          100'0'              100'1           12
                         13                   15         3.5      5          2      15       2       8
Ld                                            61           1     82
D1                                           391           1  1.046
D2                                           392           1  1.021
D3                                           393           1  1.021
D4                                           394           1  1.034
D5                                           398           1  1.033
D6                                           396           1  1.037
D7                                           399           1  1.022
D0                                           395           1   1.02
D0                                           397           1  1.045
D*                          *****                          1      1
CNB
11111400.......................
                        0.1                    1           0      0..............
*0000


*000+0.0                    000+0.0             st
...............................
                                               0 0Peak...32       0......
1234...........................................................................
                  1.12311E+79
......................*.......................................................
```

FWD DATA	*0000		2000									Radial Distances (inches)					
LR '10.5"											0	8	12	18	24	36	60
STATION	1.0000WBIW36		I4114997	Heights						Load (lbf)		Deflections (inc x 10-3)					
		565	378	216	161	116	90	62	38	8984	14.87	8.52	6.4	4.56	3.54	2.5	1.49
		567	370	215	161	117	91	63	39	9016	14.58	8.48	6.4	4.6	3.58	2.5	1.53
		758	470	283	214	157	122	86	53	12048	18.49	11.1	8.4	6.19	4.8	3.4	2.09
		948	608	359	275	203	158	111	68	15064	23.93	14.2	11	7.98	6.22	4.4	2.7
LR '10.5"																	
STATION	2.0000WBIW36		I4115497	Heights													
		555	373	217	162	118	92	64	38	8824	14.7	8.56	6.4	4.64	3.62	2.5	1.49
		558	357	211	158	117	92	65	39	8856	14.04	8.32	6.2	4.6	3.62	2.6	1.53
		751	490	290	220	161	126	88	52	11936	19.27	11.4	8.6	6.35	4.96	3.5	2.05
		941	630	378	288	213	164	114	67	14952	24.79	14.9	11	8.39	6.47	4.5	2.66
RCA '10.5"																	
STATION	3.0000WBIW36		I4115997	Heights													
		556	269	176	148	120	97	69	40	8832	10.58	6.91	5.8	4.72	3.82	2.7	1.57
		566	258	172	145	119	97	69	41	8984	10.17	6.75	5.7	4.68	3.82	2.7	1.61
		762	351	236	200	164	133	95	55	12104	13.84	9.29	7.9	6.47	5.25	3.8	2.17
		953	449	305	260	214	174	124	71	15144	17.67	12	10	8.43	6.83	4.9	2.78
RCA '10.5"																	
STATION	4.0000WBIW36		I4120397	Heights													
		559	238	159	136	109	89	64	39	8880	9.39	6.27	5.4	4.27	3.5	2.5	1.53
		562	232	156	134	109	88	64	39	8928	9.14	6.15	5.3	4.27	3.46	2.5	1.53
		758	316	214	183	148	122	87	52	12040	12.44	8.44	7.2	5.82	4.8	3.4	2.05
		951	408	279	239	194	159	114	67	15104	16.06	11	9.4	7.65	6.26	4.5	2.66
RCA '8"																	
STATION	5.0000WBIW36		I4120697	Heights													
		555	245	155	132	105	86	61	37	8824	9.64	6.11	5.2	4.15	3.38	2.4	1.45
		563	235	152	130	104	86	61	37	8936	9.27	5.99	5.1	4.11	3.38	2.4	1.45
		757	320	208	178	143	117	84	50	12024	12.6	8.2	7	5.62	4.6	3.3	1.97
		949	412	272	233	188	153	109	64	15072	16.23	10.7	9.2	7.41	6.02	4.3	2.53
RCA '8.0"																	
STATION	6.0000WBIW36		I4121097	Heights													
		555	285	162	134	107	86	61	36	8816	11.2	6.39	5.3	4.19	3.38	2.4	1.41
		562	272	159	133	105	85	61	36	8928	10.71	6.27	5.2	4.15	3.33	2.4	1.41
		753	367	220	183	146	118	84	48	11968	14.45	8.64	7.2	5.74	4.64	3.3	1.89
		945	470	287	239	193	154	109	62	15024	18.49	11.3	9.4	7.61	6.06	4.3	2.45

```
LR '10.5"
STATION      7.0000WBOW36   I4122197    Heights ..........................
                    551     416   236   174   125    96    66    40    8760  16.39   9.29   6.8  4.93  3.78   2.6  1.57
                    557     394   227   169   124    95    66    41    8848  15.53   8.92   6.7  4.89  3.74   2.6  1.61
                    751     533   309   232   170   130    91    55   11928     21   12.2   9.1  6.68  5.12   3.6  2.17
                    940     690   401   302   221   168   118    72   14936  27.18   15.8    12  8.71  6.63   4.7  2.82
LR '10.5"
STATION      8.0000WBOW36   I4125497    Heights ..........................
                    562     316   206   157   116    92    66    40    8936  12.44   8.12   6.2  4.56  3.62   2.6  1.57
                    562     305   199   153   115    91    66    40    8928  12.03   7.84     6  4.52  3.58   2.6  1.57
                    758     433   271   209   157   125    90    54   12048  17.05   10.7   8.2  6.19  4.92   3.6  2.13
                    949     576   351   274   205   162   116    69   15072  22.69   13.8    11  8.06  6.39   4.6  2.74
RCA '10.5"
STATION      9.0000WBOW45   I41258113   Heights ..........................
                    556     265   176   148   123   101    72    40    8840  10.42   6.91   5.8  4.84  3.99   2.8  1.57
                    562     256   173   146   122   100    72    41    8928  10.09   6.79   5.8   4.8  3.94   2.8  1.61
                    758     354   236   200   168   137    97    55   12040  13.92   9.29   7.9  6.59  5.41   3.8  2.17
                    950     460   307   262   219   181   127    71   15096  18.12   12.1    10  8.63  7.12     5  2.78
RCA '10.5"
STATION      10.0000WBOW45  I41301113   Heights ..........................
                    555     264   165   137   111    91    63    37    8816  10.38   6.51   5.4  4.36  3.58   2.5  1.45
                    556     255   162   135   110    91    63    37    8840  10.05   6.39   5.3  4.32  3.58   2.5  1.45
                    755     348   222   186   152   125    87    50   12000  13.71   8.72   7.3  5.98  4.92   3.4  1.97
                    947     445   287   241   197   162   113    64   15048   17.5   11.3   9.5  7.78  6.39   4.5  2.53
RCA '8"
STATION      11.0000WBOW45  I41305113   Heights ..........................
                    556     257   160   134   111    91    63    37    8832  10.13   6.31   5.3  4.36  3.58   2.5  1.45
                    559     249   157   132   110    90    63    37    8880    9.8   6.19   5.2  4.32  3.54   2.5  1.45
                    755     339   215   182   151   125    86    50   12000  13.34   8.48   7.2  5.94  4.92   3.4  1.97
                    944     433   280   237   197   162   112    64   15008  17.05     11   9.3  7.78  6.39   4.4  2.53
RCA'8.0"
STATION      12.0000WBOW45  I41308113   Heights ..........................
                    557     271   159   132   109    89    62    37    8848  10.67   6.27   5.2  4.27   3.5   2.5  1.45
                    563     259   156   131   108    88    61    37    8952  10.21   6.15   5.2  4.23  3.46   2.4  1.45
                    759     352   214   179   148   121    84    50   12056  13.88   8.44     7  5.82  4.76   3.3  1.97
                    952     457   281   236   193   159   111    64   15136     18   11.1   9.3  7.61  6.26   4.4  2.53
EOF
```

```
R80                                  10900082570UCF82536F10          2001
700031008002-03165620                328           8
                          150          0           203    305     457     610    914  1524     5.9
A:\
UCF                        TEST            TRACK
S                          12.0000WBOW45           110    113Heights   ............................
S                          12.0000WBOW45           110    113Heights   ............................
0'                         100'0'          100'1           12
                           13             15       3.5      5        2       15       2      8
Ld                                        61         1     82
D1                                       391         1  1.046
D2                                       392         1  1.021
D3                                       393         1  1.021
D4                                       394         1  1.034
D5                                       398         1  1.033
D6                                       396         1  1.037
D7                                       399         1  1.022
D0                                       395         1   1.02
D0                                       397         1  1.045
D*                         *****                     1      1
CNB
11111400........................
                          0.1              1         0      0..............
*0000


*000+0.0                   000+0.0         st
................................
                                         00Peak...32        0......
1234............................................................................
                     1.123E+79
.......................*.......................................................
******************************************************************************
................................................................................
................................................................................
```

FWD DATA	*0000	2001...................											Radial Distances (inches)				
LR	10.5"										0	8	12	18	24	36	60
STATION	1.0000WBIW36I4114997 Heights												Deflections (inc x 10-3)				
		565	378	216	161	116	90	62	38	8787	13.81	8.74	5.82	3.07	2.63	1.73	1.1
		567	370	215	161	117	91	63	39	8882	13.58	8.7	5.78	3.07	2.59	1.69	1.14
		758	470	283	214	157	122	86	53	11615	17.95	11.96	8.38	4.48	3.97	2.59	1.61
		948	608	359	275	203	158	111	68	14237	22.67	15.43	11.06	6.22	5.59	3.62	2.2
LR	10.5"																
S	2.0000WBIW36I4115497 Heights																
		555	373	217	162	118	92	64	38	8517	13.62	9.09	6.37	3.18	2.63	1.65	1.06
		558	357	211	158	117	92	65	39	8644	13.77	9.17	6.33	3.18	2.59	1.65	1.06
		751	490	290	220	161	126	88	52	11552	18.38	12.71	9.21	4.76	4.09	2.48	1.53
		941	630	378	288	213	164	114	67	14158	22.71	16.1	11.92	6.57	5.62	3.34	1.96
RCA	10.5"																
S	3.0000WBIW36I4115997 Heights																
		556	269	176	148	120	97	69	40	8135	5.39	4.48	3.85	2.55	2.91	2.24	1.33
		566	258	172	145	119	97	69	41	8167	5.39	4.44	3.81	2.51	2.87	2.2	1.29
		762	351	236	200	164	133	95	55	11011	7.99	6.61	5.74	3.85	4.33	3.3	1.88
		953	449	305	260	214	174	124	71	14634	10.78	9.05	7.87	5.43	5.94	4.52	2.55
RCA	10.5"																
S	4.0000WBIW36I4120397 Heights																
		559	238	159	136	109	89	64	39	8342	5.51	4.44	3.74	2.4	2.71	2.04	1.22
		562	232	156	134	109	88	64	39	8469	5.51	4.44	3.74	2.4	2.67	2.04	1.22
		758	316	214	183	148	122	87	52	11377	7.75	6.29	5.39	3.5	3.89	2.95	1.73
		951	408	279	239	194	159	114	67	14634	10.23	8.34	7.16	4.76	5.19	3.89	2.32
RCA	8"																
S	5.0000WBIW36I4120697 Heights																
		555	245	155	132	105	86	61	37	8183	5.19	4.33	3.62	2.12	2.63	2	1.22
		563	235	152	130	104	86	61	37	8278	5.11	4.29	3.62	2.36	2.63	1.92	1.22
		757	320	208	178	143	117	84	50	11059	7.28	5.98	5.15	3.42	3.77	2.83	1.65
		949	412	272	233	188	153	109	64	14682	9.6	8.03	6.92	4.64	5.03	3.74	2.2
RCA	8"																
S	6.0000WBIW36I4121097 Heights																
		555	285	162	134	107	86	61	36	8660	4.76	3.89	3.34	2.04	2.4	1.85	1.14
		562	272	159	133	105	85	61	36	8819	4.8	3.93	3.34	2.16	2.48	1.85	1.1
		753	367	220	183	146	118	84	48	11599	6.85	5.55	4.8	3.14	3.54	2.63	1.57
		945	470	287	239	193	154	109	62	14444	9.13	7.59	6.57	4.37	4.8	3.66	2.04

```
LR          10.5"
S           7.0000WBOW36  I4122197   Heights     ............................
                        551     416     236     174     125     96     66     40     8977   14.88   10.11    6.88    3.34    3.11    2.08    1.33
                        557     394     227     169     124     95     66     41     9105   14.84   10.03    6.81     3.3    3.03    2.04    1.37
                        751     533     309     232     170    130     91     55    11472   19.09    13.3    9.37    4.92    4.52    2.99    1.81
                        940     690     401     302     221    168    118     72    14491   23.54   16.61   11.96    6.69    6.06    3.97    2.36
LR          10.5"
S           8.0000WBOW36  I4125497   Heights     ............................
                        562     316     206     157     116     92     66     40     9438   14.52   10.66    7.12    3.38    2.99    1.88    1.18
                        562     305     199     153     115     91     66     40     9486   15.23   10.98    7.24    3.38    2.95    1.85    1.14
                        758     433     271     209     157    125     90     54    12155   19.05   14.33    9.88    5.07    4.48    2.79    1.61
                        949     576     351     274     205    162    116     69    14269   23.58   17.87   12.63    6.81    5.98     3.7    2.08
RCA         10.5"
S           9.0000WBOW45  I41258113 Heights     ............................
                        556     265     176     148     123    101     72     40     8660    6.14    4.44    3.93    2.51    3.11     2.4    1.41
                        562     256     173     146     122    100     72     41     8676     6.1    4.48    3.93    2.51    3.11     2.4    1.37
                        758     354     236     200     168    137     97     55    11409    8.77    6.37    5.62    3.74    4.44    3.38    1.92
                        950     460     307     262     219    181    127     71    15095   11.57    8.54    7.51    5.15     5.9    4.52    2.55
RCA         10.5"
S           10.0000WBOW45I41301113 Heights     ............................
                        555     264     165     137     111     91     63     37     9089    5.94    4.99    3.97     2.4    3.11    2.24    1.41
                        556     255     162     135     110     91     63     37     9248    6.14    4.99    3.97    3.07    3.07    2.28    1.41
                        755     348     222     186     152    125     87     50    11583    8.42    6.81    5.66    3.77    4.21    3.11    1.85
                        947     445     287     241     197    162    113     64    14952    11.1    8.89    7.51    5.03    5.55    4.09    2.44
RCA         8"
S           11.0000WBOW45I41305113 Heights     ............................
                        556     257     160     134     111     91     63     37     9422    5.51    4.68    3.93     2.4    2.87    2.12    1.29
                        559     249     157     132     110     90     63     37     9502    5.55    4.68    4.01    2.24    2.95    2.12    1.14
                        755     339     215     182     151    125     86     50    12140    7.48    6.45    5.51    3.62    3.97    2.87    1.73
                        944     433     280     237     197    162    112     64    14571    9.96    8.38    7.24     4.6    5.27    3.85     2.2
RCA         8"
S           12.0000WBOW45I41308113 Heights     ............................
                        557     271     159     132     109     89     62     37     9295     5.9     4.6    3.85    2.48    2.87    2.08    1.25
                        563     259     156     131     108     88     61     37     9438    6.06     4.6    3.93    2.51    2.87    2.08    1.22
                        759     352     214     179     148    121     84     50    11806    8.22    6.85    5.27    3.34    4.25    3.26    1.65
                        952     457     281     236     193    159    111     64    15032   10.78    8.18     7.2    4.72    5.03    3.62    2.12
EOF
```

Appendix D

Laboratory Test of Asphalt Concrete Resilient Modulus

```
*************************************************************
  FDOT Resilient Modulus Cores for Dr. Kwo UCF - October 2000

  Total Number of Mixtures in Experiment =  2
  Test Data Path = C:\ITLT\DATA\
*************************************************************
  MIXTURE # 1: FDOT
*************************************************************

               ********** INSTANTANEOUS **********
                    RESILIENT MODULUS (GPa)

CYCLE       T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1             2.97            3.98            3.21
  2             2.94            4.05            3.08
  3             2.94            3.95            3.08

        POISSONS RATIO: FROM RESILIENT MODULUS DATA

CYCLE                 T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1    CALCULATED:      0.37            0.35            0.33
             USED:      0.37            0.35            0.33
  2    CALCULATED:      0.36            0.32            0.35
             USED:      0.36            0.32            0.35
  3    CALCULATED:      0.36            0.34            0.35
             USED:      0.36            0.34            0.35

      (**) - Used Poissons Ratio was manually inputed

               ************** TOTAL **************
                    RESILIENT MODULUS (GPa)

CYCLE       T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1             2.60            3.54            2.83
  2             2.56            3.53            2.76
  3             2.53            3.47            2.69
```

2.61 GPa μ
.13 GPa σ

```
        POISSONS RATIO: FROM RESILIENT MODULUS DATA

CYCLE                 T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1    CALCULATED:      0.39            0.35            0.36
             USED:      0.39            0.35            0.36
  2    CALCULATED:      0.39            0.34            0.36
             USED:      0.39            0.34            0.36
  3    CALCULATED:      0.39            0.36            0.38
             USED:      0.39            0.36            0.38

      (**) - Used Poissons Ratio was manually inputed

                    NORMALIZED DEFORMATIONS

CYCLE     T1 =  25.0C              T2 =  25.0C              T3 =  25.0C
     FACE  HI  FACE  VI       FACE  HI  FACE  VI       FACE  HI  FACE  VI
  1
       3  188.   3  291.        3  152.   3  307.        6  196.   6  290.
      *1  188.  *1  291.       *1  152.  *1  307.       *4  196.  *4  290.
      *5  188.  *5  291.       *5  152.  *5  307.       *2  196.  *2  290.
      *6  233.  *6  424.       *6  223.  *6  343.       *5  211.  *5  414.
      *2  233.  *2  424.       *2  223.  *2  343.       *1  211.  *1  414.
       4  233.   4  424.        4  223.   4  343.        3  211.   3  414.

     FACE  HT  FACE  VT       FACE  HT  FACE  VT       FACE  HT  FACE  VT
  1
      #3  227.   3  339.       13  172.   3  345.        6  227.   6  332.
      .1  227.  *1  339.       t1  172.  *1  345.       *4  227.  *4  332.
      m5  227.  *5  339.        5  172.  *5  345.       *2  227.  *2  332.
```

```
      *6  274.  *6  495.       *6  260.  *6  403.       *5  249.  *5  467.
      *2  274.  *2  495.       *2  260.  *2  403.       *1  249.  *1  467.
       4  274.   4  495.        4  260.   4  403.        3  249.   3  467.

CYCLE     T1 =  25.0C              T2 =  25.0C              T3 =  25.0C
     FACE  HI  FACE  VI       FACE  HI  FACE  VI       FACE  HI  FACE  VI
  2
       3  190.   3  297.        3  153.   3  315.        6  201.   6  303.
      *1  190.  *1  297.       *1  153.  *1  315.       *4  201.  *4  303.
      *5  190.  *5  297.       *5  153.  *5  315.       *2  201.  *2  303.
      *6  233.  *6  432.       *6  215.  *6  349.       *5  224.  *5  416.
      *2  233.  *2  432.       *2  215.  *2  349.       *1  224.  *1  416.
       4  233.   4  432.        4  215.   4  349.        3  224.   3  416.

     FACE  HT  FACE  VT       FACE  HT  FACE  VT       FACE  HT  FACE  VT
  2
       3  228.  O3  340.        3  176.   3  356.        6  231.   6  343.
      *1  228.  81  340. .     *1  176.  *1  356.       *4  231.  *4  343.
      *5  228.  x5  340.       *5  176.  *5  356.       *2  231.  *2  343.
      *6  277.   6  503.       *6  257.  *6  398.       *5  258.  *5  476.
      *2  277.  *2  503.       *2  257.  *2  398.       *1  258.  *1  476.
       4  277.   4  503.        4  257.   4  398.        3  258.   3  476.

CYCLE     T1 =  25.0C           .  T2 =  25.0C              T3 =  25.0C
     FACE  HI  FACE  VI       FACE  HI  FACE  VI       FACE  HI  FACE  VI
  3
       3  189.   3  293.        3  154.   3  317.        6  203.   6  299.
      *1  189.  *1  293.       *1  154.  *1  317.       *4  203.  *4  299.
      *5  189.  *5  293.       *5  154.  *5  317.       *2  203.  *2  299.
      *6  233.  *6  429.       *6  223.  *6  343.       *5  225.  *5  425.
      *2  233.  *2  429.       *2  223.  *2  343.       *1  225.  *1  425.
       4  233.   4  429.        4  223.   4  343.        3  225.   3 .425.

     FACE  HT  FACE  VT       FACE  HT  FACE  VT       FACE  HT  FACE  VT
  3
       3  232.   3  343.        3  179.   3  357.        6  241.   6  347.
      *1  232.  *1  343.       *1  179.  *1  357.       *4  241.  *4  347.
      *5  232.  *5  343.       *5  179.  *5  357.       *2  241.  *2  347.
      *6  279.  *6  504.       *6  262.  *6  399.       *5  264.  *5  488.
      *2  279.  *2  504.       *2  262.  *2  399.       *1  264.  *1  488.
       4  279.   4  504.        4  262.  F4  399.        3  264.   3  488.

         (*) - Faces used to calculate Poissons Ratio

              RESILIENT MODULUS TEST DATA FILE NAMES

   T1 =  25.0C              T2 =  25.0C              T3 =  25.0C
   FDOT#6.txm               FDOT#8.txm               FDOT#10.txm
   FDOT#6.txm               FDOT#8.txm               FDOT#10.txm
   FDOT#6.txm               FDOT#8.txm               FDOT#10.txm

                  SPECIMEN THICKNESSES (INCHES)

   T1 =  25.0C              T2 =  25.0C'             T3 =  25.0C
      1.49                     1.52                     1.79
      1.49                     1.52                     1.79
      1.49                     1.52                     1.79

                   SPECIMEN DIAMETERS (INCHES)

   T1 =  25.0C              T2 =  25.0C              T3 =  25.0C
      3.75                     3.75                     3.74
      3.75                     3.75                     3.74
      3.75                     3.75                     3.74
```

```
*************************************************************
  FDOT Resilient Modulus Cores for Dr. Kwo UCF - October 2000

  Total Number of Mixtures in Experiment =  2
  Test Data Path = C:\ITLT\DATA\
*************************************************************
  MIXTURE # 2: FDOT
*************************************************************

          ********** INSTANTANEOUS **********
                 RESILIENT MODULUS (GPa)

CYCLE       T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1            2.90            2.90            2.90
  2            2.94            2.94            2.94
  3            2.84            2.84            2.84

      POISSONS RATIO: FROM RESILIENT MODULUS DATA

CYCLE                 T1 =  25.0C   T2 =  25.0C   T3 =  25.0C
  1     CALCULATED:   0.20          0.20          0.20
              USED:   0.20          0.20          0.20
  2     CALCULATED:   0.18          0.18          0.18
              USED:   0.18          0.18          0.18
  3     CALCULATED:   0.20          0.20          0.20
              USED:   0.20          0.20          0.20

    (**) - Used Poissons Ratio was manually inputed

          ************** TOTAL **************
                 RESILIENT MODULUS (GPa)

CYCLE       T1 =  25.0C     T2 =  25.0C     T3 =  25.0C
  1            2.52            2.52            2.52
  2            2.52            2.52            2.52
  3            2.48            2.48            2.48

      POISSONS RATIO: FROM RESILIENT MODULUS DATA

CYCLE                 T1 =  25.0C   T2 =  25.0C   T3 =  25.0C
  1     CALCULATED:   0.21          0.21          0.21
              USED:   0.21          0.21          0.21
  2     CALCULATED:   0.19          0.19          0.19
              USED:   0.19          0.19          0.19
  3     CALCULATED:   0.20          0.20          0.20
              USED:   0.20          0.20          0.20

    (**) - Used Poissons Ratio was manually inputed

                 NORMALIZED DEFORMATIONS

CYCLE     T1 =  25.0C            T2 =  25.0C            T3 =  25.0C
     FACE  HI  FACE  VI     FACE  HI  FACE  VI     FACE  HI  FACE  VI
  1
      6  156.   3  373.      6  156.   3  373.      6  156.   3  373.
     *4  156.  *1  373.     *4  156.  *1  373.     *4  156.  *1  373.
     *2  156.  *5  373.     *2  156.  *5  373.     *2  156.  *5  373.
     *5  214.  *6  412.     *5  214.  *6  412.     *5  214.  *6  412.
     *1  214.  *2  412.     *1  214.  *2  412.     *1  214.  *2  412.
      3  214.   4  412.      3  214.   4  412.      3  214.   4  412.

     FACE  HT  FACE  VT     FACE  HT  FACE  VT     FACE  HT  FACE  VT
  1
     #6  180.   3  423.     16  180.   3  423.      6  180.   3  423.
     .4  180.  *1  423.     t4  180.  *1  423.     *4  180.  *1  423.
```

```
     *5  251.  *6  480.     *5  251.  *6  480.     *5  251.  *6  480.
     *1  251.  *2  480.     *1  251.  *2  480.     *1  251.  *2  480.
      3  251.   4  480.      3  251.   4  480.      3  251.   4  480.

CYCLE     T1 =  25.0C            T2 =  25.0C            T3 =  25.0C
     FACE  HI  FACE  VI     FACE  HI  FACE  VI     FACE  HI  FACE  VI
  2
      6  156.   3  373.      6  156.   3  373.      6  156.   3  373.
     *4  156.  *1  373.     *4  156.  *1  373.     *4  156.  *1  373.
     *2  156.  *5  373.     *2  156.  *5  373.     *2  156.  *5  373.
     *5  210.  *6  428.     *5  210.  *6  428.     *5  210.  *6  428.
     *1  210.  *2  428.     *1  210.  *2  428.     *1  210.  *2  428.
      3  210.   4  428.      3  210.   4  428.      3  210.   4  428.

     FACE  HT  FACE  VT     FACE  HT  FACE  VT     FACE  HT  FACE  VT
  2
      6  184.  O3  428.      6  184.   3  428.      6  184.   3  428.
     *4  184.  11  428.     *4  184.  *1  428.     *4  184.  *1  428.
     *2  184.  t5  428.     *2  184.  *5  428.     *2  184.  *5  428.
     *5  251.   6  500.     *5  251.  *6  500.     *5  251.  *6  500.
     *1  251.  *2  500.     *1  251.  *2  500.     *1  251.  *2  500.
      3  251.   4  500.      3  251.   4  500.      3  251.   4  500.

CYCLE     T1 =  25.0C            T2 =  25.0C            T3 =  25.0C
     FACE  HI  FACE  VI     FACE  HI  FACE  VI     FACE  HI  FACE  VI
  3
      6  165.   3  369.      6  165.   3  369.      6  165.   3  369.
     *4  165.  *1  369.     *4  165.  *1  369.     *4  165.  *1  369.
     *2  165.  *5  369.     *2  165.  *5  369.     *2  165.  *5  369.
     *5  217.  *6  437.     *5  217.  *6  437.     *5  217.  *6  437.
     *1  217.  *2  437.     *1  217.  *2  437.     *1  217.  *2  437.
      3  217.   4  437.      3  217.   4  437.      3  217.   4  437.

     FACE  HT  FACE  VT     FACE  HT  FACE  VT     FACE  HT  FACE  VT
  3
      6  191.   3  427.      6  191.   3  427.      6  191.   3  427.
     *4  191.  *1  427.     *4  191.  *1  427.     *4  191.  *1  427.
     *2  191.  *5  427.     *2  191.  *5  427.     *2  191.  *5  427.
     *5  252.  *6  512.     *5  252.  *6  512.     *5  252.  *6  512.
     *1  252.  *2  512.     *1  252.  *2  512.     *1  252.  *2  512.
      3  252.   4  512.      3  252.  F4  512.      3  252.   4  512.

      (*) - Faces used to calculate Poissons Ratio

            RESILIENT MODULUS TEST DATA FILE NAMES

   T1 =  25.0C             T2 =  25.0C             T3 =  25.0C
   FDOT#12.txm             FDOT#12.txm             FDOT#12.txm
   FDOT#12.txm             FDOT#12.txm             FDOT#12.txm
   FDOT#12.txm             FDOT#12.txm             FDOT#12.txm

              SPECIMEN THICKNESSES (INCHES)

   T1 =  25.0C             T2 =  25.0C             T3 =  25.0C
     1.59                    1.59                    1.59
     1.59                    1.59                    1.59
     1.59                    1.59                    1.59

               SPECIMEN DIAMETERS (INCHES)

   T1 =  25.0C             T2 =  25.0C             T3 =  25.0C
     3.72                    3.72                    3.72
     3.72                    3.72                    3.72
     3.72                    3.72                    3.72
```

Appendix E

Samples of Kenlayer Program Output

```
    NUMBER OF PROBLEMS TO BE SOLVED =    1


    ********************************************************************************************
    *                                                                                          *
    *     FDOT Project RCA Section 8 inc.                                                      *
    *                                                                                          *
    ********************************************************************************************



    MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

    NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

    NUMBER OF PERIODS PER YEAR (NPY) =    1

    NUMBER OF LOAD GROUPS (NLG) =    1

         TOLERANCE FOR INTEGRATION (DEL) -- =    .00100

         NUMBER OF LAYERS (NL)------------- =         3

         NUMBER OF Z COORDINATES (NZ)------ =         3

         LIMIT OF INTEGRATION CYCLES (ICL)- =        80

         COMPUTING CODE (NSTD)------------- =         9

         THICKNESSES OF LAYERS (TH) ARE         :     4.00000     8.00000

         POISSON'S RATIOS OF LAYERS (PR) ARE    :      .35000      .30000      .40000

         VERTICAL COORDINATES OF POINTS (ZC) ARE:      .00000     4.00000    12.00100

         ALL INTERFACES ARE FULLY BONDED

         FOR PERIOD NO.  1 ELASTIC MODULI OF LAYERS ARE:    .380000E+06    .195000E+06    .300000E+05

         LOAD GROUP NO.  1 HAS 1 CONTACT AREAS
         CONTACT RADIUS (CR)--------------- =   6.00000
         CONTACT PRESSURE (CP)------------- = 107.00000
         RADIAL COORDINATES OF THE 7 POINTS (RC) ARE  :      .00000     8.00000    12.00000    18.00000    24.00000    36.00000
                                                           60.00000

         PERIOD NO.  1  LOAD GROUP NO.  1

  RADIAL     VERTICAL    VERTICAL    VERTICAL     RADIAL    TANGENTIAL    SHEAR      VERTICAL     RADIAL    TANGENTIAL    SHEAR
COORDINATE  COORDINATE     DISP.      STRESS      STRESS      STRESS      STRESS      STRAIN      STRAIN      STRAIN      STRAIN
   .00000      .00000   .1180E-01   .1501E+03   .1979E+03   .1979E+03   .0000E+00   .3040E-04   .2003E-03   .2003E-03   .0000E+00
   .00000     4.00000   .1103E-01   .7520E+02  -.7066E+01  -.7066E+01   .0000E+00   .2109E-03  -.8135E-04  -.8135E-04   .0000E+00
```

```
      .00000    12.00100   .9177E-02   .1281E+02   .2921E+00   .2921E+00   .0000E+00   .4191E-03  -.1649E-03  -.1649E-03   .0000E+00
     8.00000      .00000   .8906E-02   .3315E+02   .5830E+02   .7227E+02  -.3973E-14  -.3302E-04   .5631E-04   .1060E-03  -.2823E-19
     8.00000     4.00000   .8680E-02   .1519E+02   .2595E+02   .1987E+01   .2397E+02   .1424E-04   .5247E-04  -.3266E-04   .1703E-03
     8.00000    12.00100   .8021E-02   .8479E+01   .1765E+01   .3752E+00   .3298E+01   .2541E-03  -.5922E-04  -.1241E-03   .3078E-03
    12.00000      .00000   .7635E-02   .1579E+02   .3267E+02   .4345E+02   .6276E-15  -.2855E-04   .3141E-04   .6971E-04   .4459E-20
    12.00000     4.00000   .7310E-02   .2447E+01   .1737E+02   .4980E+01   .1199E+02  -.1415E-04   .3888E-04  -.5150E-05   .8521E-04
    12.00000    12.00100   .7051E-02   .5709E+01   .2311E+01   .4319E+00   .3059E+01   .1537E-03  -.4850E-05  -.9253E-04   .2855E-03
    18.00000      .00000   .5802E-02   .1486E+01   .1457E+01   .1832E+02  -.2013E-14  -.1431E-04  -.1441E-04   .4550E-04  -.1430E-19
    18.00000     4.00000   .5839E-02   .7040E+00   .6591E+01   .4245E+01   .5456E+01  -.8128E-05   .1279E-04   .4451E-05   .3877E-04
    18.00000    12.00100   .5743E-02   .3165E+01   .2212E+01   .4421E+00   .2137E+01   .7013E-04   .2563E-04  -.5696E-04   .1995E-03
    24.00000      .00000   .4741E-02   .7847E+00  -.2651E+01   .1076E+02   .4732E-14  -.5408E-05  -.1761E-04   .3005E-04   .3362E-19
    24.00000     4.00000   .4747E-02   .4722E+00   .2723E+01   .3106E+01   .2697E+01  -.4126E-05   .3871E-05   .5230E-05   .1916E-04
    24.00000    12.00100   .4710E-02   .1833E+01   .1775E+01   .3768E+00   .1433E+01   .3239E-04   .2972E-04  -.3555E-04   .1337E-03
    36.00000      .00000   .3267E-02  -.2636E+00  -.4986E+01   .3311E+01  -.1414E-14   .8488E-06  -.1593E-04   .1355E-04  -.1005E-19
    36.00000     4.00000   .3276E-02   .1544E+00   .2690E+00   .1578E+01   .5937E+00  -.1295E-05  -.8876E-06   .3762E-05   .4218E-05
    36.00000    12.00100   .3281E-02   .6178E+00   .1011E+01   .2082E+00   .6530E+00   .4340E-05   .2268E-04  -.1478E-04   .6095E-04
    60.00000      .00000   .1866E-02  -.6673E-01  -.2257E+01   .6919E+00   .6990E-15   .1266E-05  -.6515E-05   .3961E-05   .4967E-20
    60.00000     4.00000   .1867E-02   .6566E-02  -.2924E+00   .5483E+00  -.5243E-01  -.2184E-06  -.1281E-05   .1706E-05  -.3726E-06
    60.00000    12.00100   .1877E-02   .4569E-01   .2918E+00   .4635E-01   .1413E+00  -.2986E-05   .8500E-05  -.2955E-05   .1318E-04
```

```
    NUMBER OF PROBLEMS TO BE SOLVED =    1


    ********************************************************************************************
    *                                                                                          *
    *     FDOT Project RCA Section 10.5 inc.                                                   *
    *                                                                                          *
    ********************************************************************************************



    MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

    NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

    NUMBER OF PERIODS PER YEAR (NPY) =    1

    NUMBER OF LOAD GROUPS (NLG) =    1

         TOLERANCE FOR INTEGRATION (DEL) -- =    .00100

         NUMBER OF LAYERS (NL)------------- =         3

         NUMBER OF Z COORDINATES (NZ)------ =         3

         LIMIT OF INTEGRATION CYCLES (ICL)- =        80

         COMPUTING CODE (NSTD)------------- =         9

         THICKNESSES OF LAYERS (TH) ARE         :     4.00000    10.50000

         POISSON'S RATIOS OF LAYERS (PR) ARE    :      .35000      .30000      .40000

         VERTICAL COORDINATES OF POINTS (ZC) ARE:      .00000     4.00000    14.50010

         ALL INTERFACES ARE FULLY BONDED

         FOR PERIOD NO.  1 ELASTIC MODULI OF LAYERS ARE:    .380000E+06    .195000E+06    .300000E+05

         LOAD GROUP NO.  1 HAS 1 CONTACT AREAS
         CONTACT RADIUS (CR)--------------- =   6.00000
         CONTACT PRESSURE (CP)------------- = 107.00000
         RADIAL COORDINATES OF THE 7 POINTS (RC) ARE  :      .00000     8.00000    12.00000    18.00000    24.00000    36.00000
                                                           60.00000

         PERIOD NO.  1  LOAD GROUP NO.  1

  RADIAL     VERTICAL    VERTICAL    VERTICAL     RADIAL    TANGENTIAL    SHEAR      VERTICAL     RADIAL    TANGENTIAL    SHEAR
COORDINATE  COORDINATE     DISP.      STRESS      STRESS      STRESS      STRESS      STRAIN      STRAIN      STRAIN      STRAIN
   .00000      .00000   .1072E-01   .1501E+03   .1874E+03   .1874E+03   .0000E+00   .4981E-04   .1823E-03   .1823E-03   .0000E+00
   .00000     4.00000   .9918E-02   .7764E+02  -.3769E+01  -.3769E+01   .0000E+00   .2113E-03  -.7796E-04  -.7796E-04   .0000E+00
```

```
      .00000    14.50010   .7782E-02   .9416E+01   .1178E+00   .1178E+00   .0000E+00   .3107E-03  -.1232E-03  -.1232E-03   .0000E+00
     8.00000      .00000   .8027E-02   .3315E+02   .5311E+02   .6532E+02  -.1910E-15  -.2184E-04   .4905E-04   .9245E-04  -.1357E-20
     8.00000     4.00000   .7787E-02   .1597E+02   .2843E+02   .4457E+01   .2193E+02   .1174E-04   .5601E-04  -.2917E-04   .1558E-03
     8.00000    14.50010   .7006E-02   .6760E+01   .1086E+01   .1974E+00   .2358E+01   .2082E-03  -.5657E-04  -.9803E-04   .2201E-03
    12.00000      .00000   .6930E-02   .1579E+02   .3030E+02   .3921E+02   .1309E-14  -.2245E-04   .2907E-04   .6073E-04   .9299E-20
    12.00000     4.00000   .6615E-02   .2398E+01   .1906E+02   .6841E+01   .1034E+02  -.1754E-04   .4164E-04  -.1757E-05   .7347E-04
    12.00000    14.50010   .6309E-02   .4860E+01   .1563E+01   .2578E+00   .2370E+01   .1377E-03  -.1615E-04  -.7704E-04   .2212E-03
    18.00000      .00000   .5770E-02   .7240E+01   .1602E+02   .2241E+02  -.1303E-14  -.1634E-04   .1485E-04   .3754E-04  -.9258E-20
    18.00000     4.00000   .5420E-02   .3733E+00   .7315E+01   .5484E+01   .4863E+01  -.1081E-04   .1386E-04   .7350E-05   .3455E-04
    18.00000    14.50010   .5306E-02   .2900E+01   .1681E+01   .3050E+00   .1815E+01   .7019E-04   .1329E-04  -.5091E-04   .1694E-03
    24.00000      .00000   .4514E-02   .7847E+00  -.6269E-01   .1086E+02  -.2360E-14  -.7876E-05  -.1089E-04   .2790E-04  -.1677E-19
    24.00000     4.00000   .4527E-02   .3004E+00   .2964E+01   .3998E+01   .2715E+01  -.5622E-05   .3840E-05   .7515E-05   .1929E-04
    24.00000    14.50010   .4473E-02   .1804E+01   .1458E+01   .2939E+00   .1292E+01   .3678E-04   .2061E-04  -.3369E-04   .1206E-03
    36.00000      .00000   .3246E-02  -.2636E+00  -.3591E+01   .3885E+01   .1940E-14  -.9644E-06  -.1278E-04   .1377E-04   .1378E-19
    36.00000     4.00000   .3259E-02   .1439E+00   .1496E+00   .2051E+01   .8222E+00  -.1648E-05  -.1628E-05   .5127E-05   .5842E-05
    36.00000    14.50010   .3253E-02   .7370E+00   .9388E+00   .2007E+00   .6645E+00   .9374E-05   .1879E-04  -.1565E-04   .6202E-04
    60.00000      .00000   .1912E-02  -.6673E-01  -.2301E+01   .8725E+00   .5975E-15   .1140E-05  -.6797E-05   .4477E-05   .4246E-20
    60.00000     4.00000   .1912E-02   .1655E-01  -.5513E+00   .6456E+00   .8129E-02  -.4331E-07  -.2061E-05   .2192E-05   .5776E-07
    60.00000    14.50010   .1922E-02   .1062E+00   .3396E+00   .6132E-01   .1817E+00  -.1808E-05   .9088E-05  -.3900E-05   .1696E-04
```

```
    NUMBER OF PROBLEMS TO BE SOLVED =    1

    ********************************************************************************************
    *                                                                                          *
    *     FDOT Project LR Section 10.5 inc.                                                    *
    *                                                                                          *
    ********************************************************************************************


    MATL = 1 FOR LINEAR ELASTIC LAYERED SYSTEM

    NDAMA = 0, SO DAMAGE ANALYSIS WILL NOT BE PERFORMED

    NUMBER OF PERIODS PER YEAR (NPY) =    1

    NUMBER OF LOAD GROUPS (NLG) =    1

         TOLERANCE FOR INTEGRATION (DEL) -- =    .00100

         NUMBER OF LAYERS (NL)------------- =         3

         NUMBER OF Z COORDINATES (NZ)------ =         3

         LIMIT OF INTEGRATION CYCLES (ICL)- =        80

         COMPUTING CODE (NSTD)------------- =         9

         THICKNESSES OF LAYERS (TH) ARE         :     4.00000    10.50000

         POISSON'S RATIOS OF LAYERS (PR) ARE    :      .35000      .30000      .40000

         VERTICAL COORDINATES OF POINTS (ZC) ARE:      .00000     4.00000    14.50010

         ALL INTERFACES ARE FULLY BONDED

         FOR PERIOD NO.  1 ELASTIC MODULI OF LAYERS ARE:    .380000E+06    .600000E+05    .300000E+05

         LOAD GROUP NO.  1 HAS 1 CONTACT AREAS
         CONTACT RADIUS (CR)--------------- =   6.00000
         CONTACT PRESSURE (CP)------------- = 107.00000
         RADIAL COORDINATES OF THE 7 POINTS (RC) ARE  :      .00000     8.00000    12.00000    18.00000    24.00000    36.00000
                                                           60.00000

           PERIOD NO.  1  LOAD GROUP NO.  1

  RADIAL     VERTICAL    VERTICAL    VERTICAL     RADIAL    TANGENTIAL    SHEAR      VERTICAL     RADIAL    TANGENTIAL    SHEAR
COORDINATE  COORDINATE     DISP.      STRESS      STRESS      STRESS      STRESS      STRAIN      STRAIN      STRAIN      STRAIN
   .00000      .00000   .1607E-01   .1501E+03   .2697E+03   .2697E+03   .0000E+00  -.1019E-03   .3231E-03   .3231E-03   .0000E+00
   .00000     4.00000   .1525E-01   .6000E+02  -.1167E+03  -.1167E+03   .0000E+00   .3729E-03  -.2549E-03  -.2549E-03   .0000E+00
   .00000    14.50010   .9534E-02   .1347E+02  -.4677E-02  -.4677E-02   .0000E+00   .4491E-03  -.1797E-03  -.1797E-03   .0000E+00
  8.00000      .00000   .1130E-01   .3315E+02   .6787E+02   .9365E+02   .8251E-14  -.6152E-04   .6182E-04   .1534E-03   .5862E-19
  8.00000     4.00000   .1089E-01   .1848E+02   .2207E+02  -.3533E+02   .1630E+02   .6085E-04   .7360E-04  -.1303E-03   .1158E-03
  8.00000    14.50010   .8350E-02   .9412E+01   .1338E+01   .1502E-01   .3577E+01   .2957E-03  -.8111E-04  -.1428E-03   .3339E-03
 12.00000      .00000   .8320E-02  -.4240E+01  -.1820E+02   .2915E+02   .1900E-14  -.2124E-04  -.7084E-04   .9737E-04   .1350E-19
 12.00000     4.00000   .8411E-02   .5527E+01   .3347E+02  -.7620E+01   .8828E+01  -.9264E-05   .9001E-04  -.5597E-04   .6273E-04
 12.00000    14.50010   .7281E-02   .6386E+01   .2044E+01   .3916E-01   .3623E+01   .1851E-03  -.1755E-04  -.1111E-03   .3381E-03
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  18.00000      .00000   .6080E-02   .1486E+01  -.9880E+01   .1477E+02   .2926E-14  -.5923E-06  -.4097E-04   .4660E-04   .2079E-19
  18.00000     4.00000   .6101E-02   .9017E+00   .1808E+02   .9636E+00   .3692E+01  -.1517E-04   .4586E-04  -.1495E-04   .2623E-04
  18.00000    14.50010   .5778E-02   .3215E+01   .2243E+01   .7429E-01   .2667E+01   .7627E-04   .3091E-04  -.7030E-04   .2489E-03
  24.00000      .00000   .4673E-02  -.2238E+01  -.1073E+02   .5525E+01  -.2373E-15  -.1101E-05  -.3125E-04   .2648E-04  -.1686E-20
  24.00000     4.00000   .4718E-02   .2122E+00   .8679E+01   .1869E+01   .1729E+01  -.9157E-05   .2092E-04  -.3270E-05   .1229E-04
  24.00000    14.50010   .4622E-02   .1612E+01   .1874E+01   .9284E-01   .1706E+01   .2751E-04   .3974E-04  -.4339E-04   .1593E-03
  36.00000      .00000   .3165E-02   .2812E+00  -.3331E+01   .3348E+01  -.1994E-15   .7240E-06  -.1211E-04   .1162E-04  -.1417E-20
  36.00000     4.00000   .3164E-02   .6165E-01   .2433E+01   .1434E+01   .4479E+00  -.3400E-05   .5026E-05   .1475E-05   .3182E-05
  36.00000    14.50010   .3167E-02   .4673E+00   .1052E+01   .8542E-01   .6843E+00   .4068E-06   .2771E-04  -.1742E-04   .6387E-04
  60.00000      .00000   .1843E-02   .7373E-01  -.1213E+01   .1063E+01   .1629E-15   .3322E-06  -.4240E-05   .3848E-05   .1157E-20
  60.00000     4.00000   .1841E-02   .3719E-02   .2622E+00   .6777E+00   .3272E-01  -.8559E-06   .6241E-07   .1538E-05   .2325E-06
  60.00000    14.50010   .1855E-02   .5020E-01   .3237E+00   .4150E-01   .1432E+00  -.3195E-05   .9566E-05  -.3601E-05   .1337E-04
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